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CCVT modelling failure mode investigation and impact on relay operation

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SUMMARY

The appropriate operation of substation assets is essential for reliable operation of the grid. Instrument transformers play a vital role in obtaining the measurement data on the primary circuits, which serve as fundamental components of grid operation. These include Capacitor Coupled Voltage Transformers (CCVT), Current Transformers (CT), etc. Currently, numerous aged instrument transformers operate in power substations. Much industry focus has been given to better monitor and maintain these devices, which are critical to reliability of transmission operations. In this paper, American Electric Power (AEP) focuses on CCVT modelling, our investigation of CCVT failure modes and related impacts to the relay operation.

This paper proposes a detailed CCVT model built in the PSCAD/EMTDC platform to simulate and identify different failure modes of CCVT. A CCVT consists of five essential components: two capacitors across which the transmission line signal is split, an inductive element to tune the device to the line frequency, a voltage transformer to isolate and further step down the voltage for metering devices or protective relays, and a Ferroresonance Suppression Circuit (FSC), which filters out subsynchronous oscillation. The condition of each of these elements has a predictable impact on the overall performance and accuracy of CCVT. Properly modelling the CCVT will simulate the behaviour of CCVT under different fault conditions. Furthermore, the simulation results can be used to better understand how different failure modes affect the waveforms of voltage measurements. This paper outlines a major AEP effort to develop a detailed PSCAD model of CCVT for transient study and investigation of CCVT failure mode.

Relay mis-operation events related to CCVT failure are investigated as a benchmark for the proposed model. Understanding the root cause of the CCVT related relay mis-operation and the relationship between CCVT failure and voltage measurements will help develop accurate CCVT model and help prevent CCVT failure in the future. This paper outlines field examples of relay tripping caused by CCVT failures. Various sources of data (such relay/comtrade, SCADA, and simulated PMU data) are used to demonstrate the CCVT failure modes. The simulated PMU data is obtained using the proposed PSCAD CCVT model. The PSCAD simulation reproduces the response of measured voltage on the progress of CCVT failures, from subtle damages to catastrophic failure. The simulated PMU data from PSCAD can also be used to identify those failure modes. Analysis of those failure modes is illustrated.

KEYWORDS

CCVT modelling, CCVT failure mode, Relay mis-operation.

1. Introduction

The appropriate operation of substation assets is essential for the reliable operation of the power grid. Instrument transformers play a vital role in obtaining the measurement data on the primary circuits. These serve as fundamental components of the grid operation [1, 2]. This includes Capacitor Coupled Voltage Transformers (CCVT), Current Transformers (CT), etc.

A CCVT consists of five essential components: two capacitors across which the transmission line signal is split, an inductive element to tune the device to the line frequency, a voltage transformer to isolate and further step down the voltage for metering devices or a protective relay and a Ferroresonance suppression circuit to filter out subsynchronous oscillation. The capacitors can lower the system voltages as an input for the inductive element, whose output signal is then isolated and reduced by the step-down transformer. The lower signal can eventually be used for protection and measurement.

CCVTs have been widely used within transmission power systems for applications ranging from high-voltage to ultrahigh-voltage, due to their smaller size, lower cost and to avoid ferroresonance [3, 4]. However, compared to a potential transformer, a CCVT has a higher probability of inaccurate measurement and insulation faults, due to the existence of capacitor dividers. In addition, numerous aged CCVTs currently operate in the substations across North America, which poses a critical potential threat to the reliability of grid operations [5]. Hence, much attention has been given to better monitor and maintain those prone-to-failure CCVTs. Many previous works have been dedicated to the research of CCVT measurement error, equipment failure and its failure patterns.

A steady-state CCVT circuit model was developed, with concentration on the measurement error caused by system frequency and secondary burden change [6]. As illustrated in [7], the modelling of capacitor voltage transformer and the simulation of its behaviour during transients using PSCAD/EMTDC was explored in detail. The failure of the CCVT equipment may result in unexpected outages of transmission lines [8].

Phasor Measurement Units (PMUs) provide high-resolution measurements (as fast as 30 or 60 frames per second), which can better capture the equipment conditions than Remote Terminal Units (RTUs) [9]. In [9], a synchrophasor-based substation level linear state estimator that was developed to identify the bad CCVT measurement, which allows the application to detect failing CCVT equipment. This application can provide early warnings to the maintenance crew before the CCVT fails. A set of data-driven methods are proposed to detect, identify and locate faults in [10], which can be leveraged to CCVT failure recognition. Research on measurement errors of a CCVT caused by insulation variation are presented in [11, 12]. It demonstrates that the insulation parameters are directly relevant to the measurement errors of a CCVT.

Few papers above provides a comprehensive modelling of a CCVT to model failure modes. In this paper, we focus on the detailed CCVT modelling, investigation of CCVT failure mode and root cause, and the impact of failure on relay operations. The detailed CCVT model is developed using PSCAD. Various simulations are conducted to mimic the actual CCVT failures. This paper presents the failure modes and root causes. Another emphasis is placed on the impact of CCVT failure to the overvoltage protection and distance protection. Two real malfunction of relays tripping 765kV transmission lines which were caused by a CCVT failure are illustrated.

The rest of the paper is organized as follows. Section 2 of this paper provides a comprehensive CCVT modelling methodology. A detailed CCVT model has been developed using PSCAD. In Section 3, we investigate various kinds of CCVT failure modes and their impacts on relay operation. Case studies with PSCAD simulated data and actual PMU data are presented in Section 4. We draw the conclusion in Section 5.

2. CCVT modelling

A detailed CCVT model contains five main components, as illustrated in Figure 1: 1) C1 as the high voltage capacitance of the capacitor voltage divider; 2) C2 as the intermediate voltage capacitance of the capacitor voltage divider; 3) Lc as the compensating reactor; 4) PT as the intermediate potential transformer; and 5) FSC as the Ferroresonance suppression circuit. Each of these components may get damaged during daily operation, which can lead to CCVT failure, so the CCVT failure mode simulation requires a detailed model of each part.

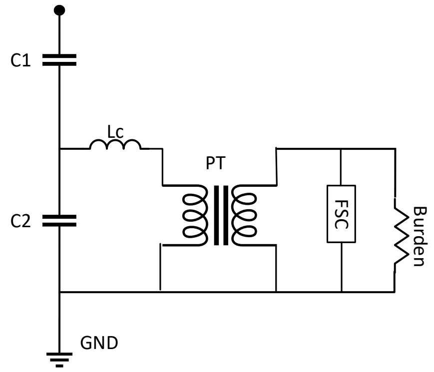

Figure 1 CCVT Circuit Representation

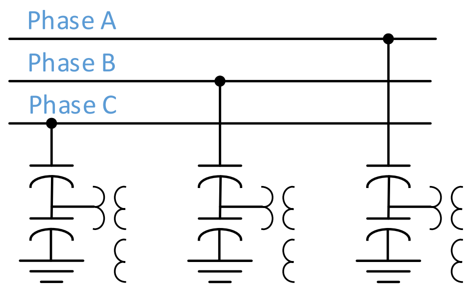

Figure 2 Schematics of CCVT

A CCVT is typically constructed as a single-phase device and is connected in shunt with transmission lines to monitor the phase-to-ground voltage, as demonstrated in Figure 2. C1 and C2 are made of series coupling capacitor stacks. They function as a voltage divider. The voltage divider helps to step the line voltage, usually above 138kV, down to an intermediate-level voltage $C1 * V/(C1 + C2)$, typically 5 to 15kV. [13] The resistance of capacitors are neglected in the simulation since the losses in modern capacitors are less than 0.2% [14]. To represent short-circuit or damage of capacitor stacks, the value of C1 and C2 can be modelled as equation (1):

$$C_{actually} = \frac{N_{total}}{N_{total} - N_{damaged}} * C_{stack} \quad (1)$$

Where, $C_{actually}$ is the actual value of C1 or C2; N_{total} is the total number of stacks in C1 or C2; C_{stack} is the capacitance of each stack in C1 or C2; $N_{damaged}$ is the number of stacks that were damaged or short circuited.

The function of Lc is to minimize the equivalent source impedance for PT and avoid phase shifts at 60 Hz. Therefore, Lc is usually tuned to the capacitance C1||C2.

The intermediate step-down transformer PT is similar to a potential transformer and is connected to the voltage divider through a compensating reactor. The PT will further reduce the voltage down to the normal relaying voltage, typically $115/\sqrt{3}$ volts. An important feature of the potential transformer to model is its nonlinear magnetic saturation in iron cores. The PT saturation can cause inaccuracy of measurements on its secondary side, when line voltage is higher than the knee point voltage. In addition, when a reclose occurs in a light burden condition, the interaction between capacitance and inductance may lead to subsynchronous oscillation on the secondary side -- when the flux density is at or near saturation and no FSC is properly designed.

Paper [15] described two EMTDC models to represent the magnetizing branch of the transformer-equivalent circuit. The first model consists of a nonlinear inductor in parallel with a nonlinear resistor derived from the saturation curves for the transformer, while the second uses a current source based on core flux equations and an iterative technique to calculate the voltage/current relationship. Both of those methods have drawbacks. The first model requires revaluation of the overall system conductance matrix, and the second model requires iterative calculation, which slows the simulation. To accelerate the simulation speed, we represent the magnetizing branch in our study by a current source, as shown in Figure 3. The magnetizing current is injected to the primary of the PT, based on the saturation curve for the transformer. The hysteresis current, or eddy current, can be set in the transformer model in PSCAD.

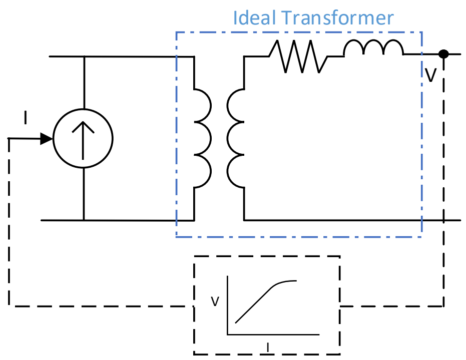

Figure 3 Equivalent circuit for the magnetic branch

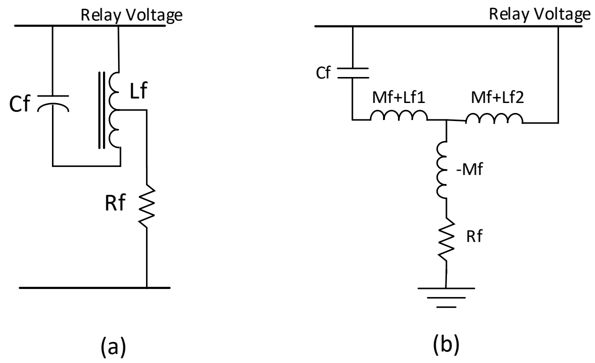

Figure 4 (a) Physical design of active FSC (b) Mathematical equivalent circuit of active FSC

Two operational modes are available for the FSC design: active and passive [16, 7, 17, 18]. An active FSC is basically a series-parallel RLC filter, which consists of a tuneable mutual coupling inductor, as shown in Figure 4(a). Figure 4(b) shows the equivalent circuit for active FSC. The mutual coupling inductor in Figure 4(a) can be represented by inductors Lf1 and Lf2, with a mutual coupling Mf in Figure 4(b). The active FSC can be tuned to act as an open circuit around rated frequency, to pass the fundamental frequency, as shown in Figure 5.

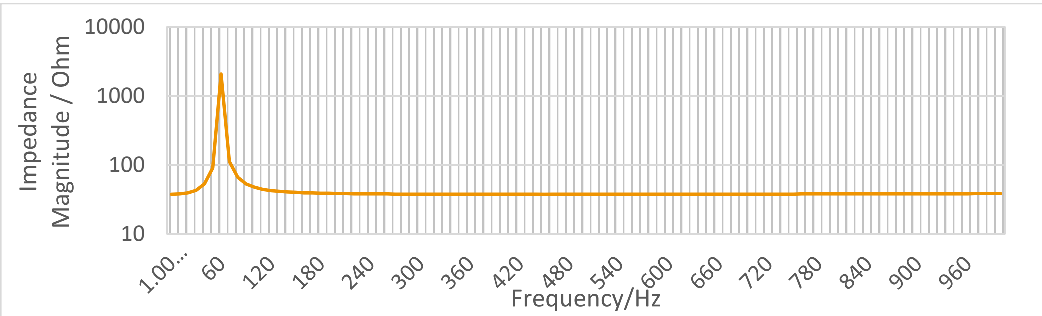

Figure 5 Impedance magnitude frequency characteristic of active FSC

Each of these elements has a predictable impact on the overall accuracy of a CCVT. To better understand how different failure modes affect the waveform of voltage measurement, a 765kV station bus has been built in PSCAD based on an existing substation (using our detailed CCVT model). The CCVT model represents all five components with the appropriate EMTDC model. The model and testing of the model are demonstrated in the case studies section (4) below.

3. Failure mode investigation and impact on relay operation

A. Failure mode

C1 and C2 are the most vulnerable components in a CCVT, for they experience more stress as they are on the high voltage side. This is especially true when aging and degrading capacitor stacks are exposed to overvoltages during switching or lightning transients. Note that both C1 and C2 are composed of capacitor stacks. These individual capacitor stacks usually start to fail one-by-one before enough damage accumulates. This could lead to cascading failure of the full CCVT. A shortage on C1 will cause the measured voltage to increase, while a shortage on capacitors of C2 will cause the measured voltage to decrease.

The FSC is another element of CCVT that commonly fails. When a FSC becomes open-circuited, the measured waveform may show distortion and overvoltage when ferroresonance oscillation takes place between capacitances and the iron core nonlinear inductance.

B. Impact on relay operation

i. Voltage protection

A normal operating system usually maintains its voltage between 0.95 – 1.05 p.u., especially for high voltage (HV) or extra high voltage (EHV) lines, to ensure an adequate power supply and to avoid extra stress on the insulation of the power system equipment. Many line relays have overvoltage and under voltage protection logic to protect equipment on the system. The logic should function well when the voltage measurements are accurate.

However, when a CCVT has short-circuited stacks in C1, it will lose accuracy while its measured voltage will rise up which may trigger relay's overvoltage protection logic by mistake. Figure 6 shows a relay record of a relay mis-operation event which tripped a 765kV line, which was caused by a CCVT failure on C1.

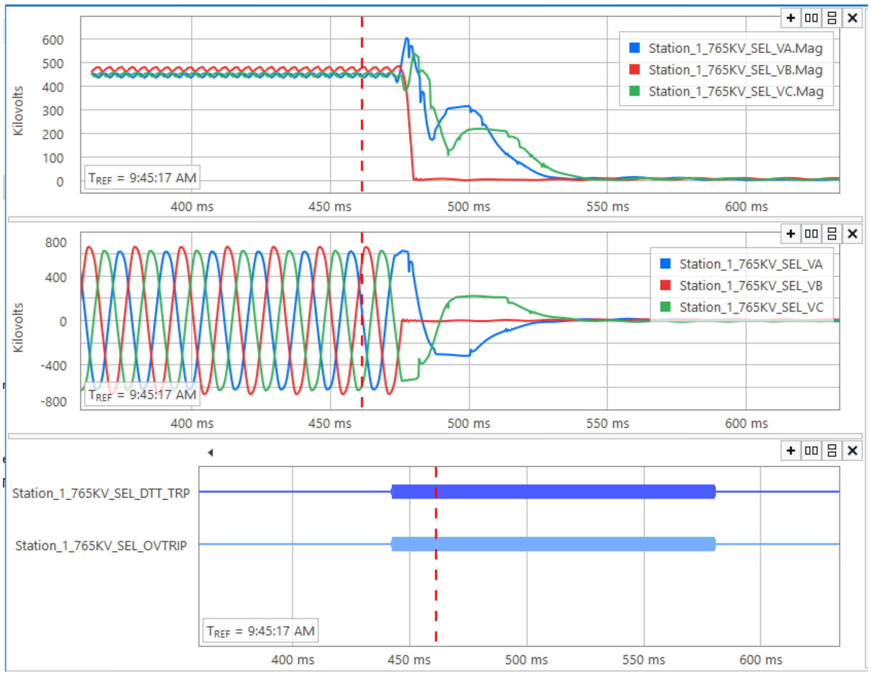

Figure 6 765 kV Transmission line tripped by over-voltage protection due to CCVT failure in C1

Various sources of data, such relay/COMTRADE, and SCADA data can be used to demonstrate the CCVT failure modes. The recorded relay/COMTRADE data has extremely high resolution which can capture very subtle changes in the measurements.

However, the relay COMTRADE data is event-driven, and so there is limited availability of this data. Unlike COMTRADE file data, SCADA data can provide continuous real-time measurements. For example, Figure 7 shows the seven-hour voltage magnitude profile of the failed CCVT, as recorded by the SCADA system. In this case the inaccuracy of the CCVT was not caused by a sudden fault, but by a step-by-step damage accumulating over time in C1.

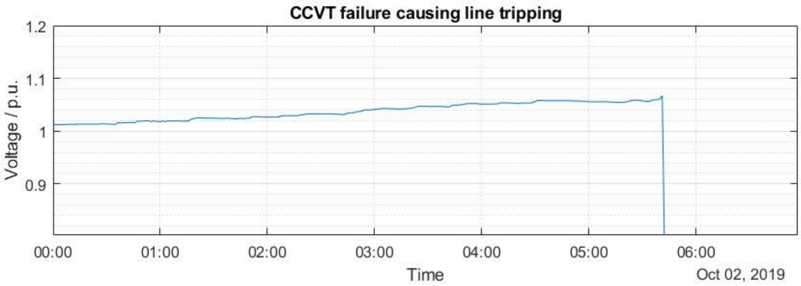

Figure 7 SCADA record of the voltage measurement before failure

A CCVT failure on its low voltage capacitor bank will cause a voltage drop, and may trigger the under-voltage protection logic by mistake. When an under voltage protection scheme is not in place, the damage of any capacitor stack in C2 will put more electrical pressure to other series-connected capacitor stacks. The CCVT may eventually fail catastrophically if the stress lasts long enough. For example, Figure 8 shows an event in which accumulated damage on C2 led to the catastrophic failure of a CCVT, which caused a 765kV transformer to trip. The voltage output from the CCVT began decreasing in steps as seen in Figure 9. This behavior is indicative of capacitor stacks in C2 being shorted. The remaining stacks subsequently starting seeing higher voltage stresses which led to further stacks shorting and ultimately to the failure of the CCVT.

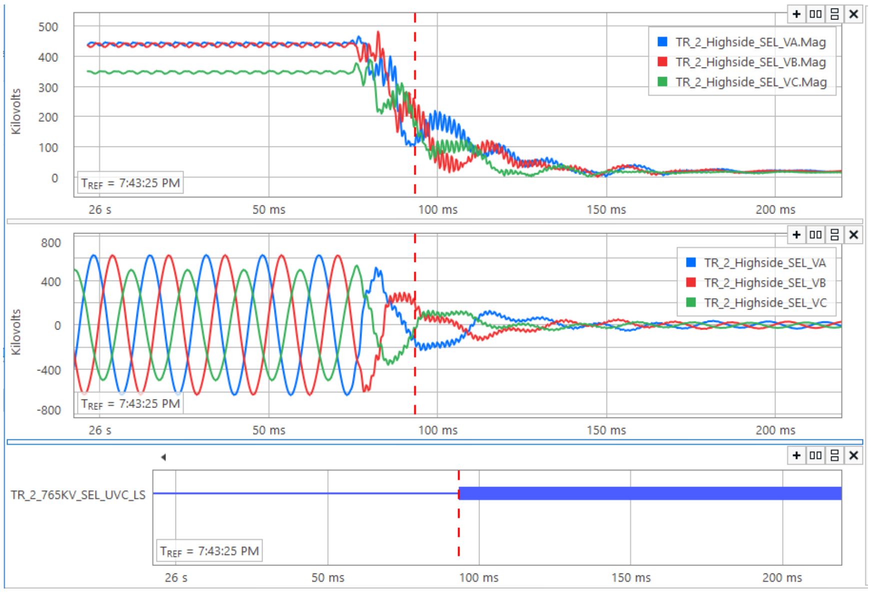

Figure 8 765kV Transformer high side tripped because of CCVT failure in C2

Figure 9 SCADA record of the voltage measurement before CCVT failure

ii. Distance protection

Distance (impedance) protection relays calculate the real-time line impedance, based on current and voltage measurements. The calculated line impedance may fall into one of the protective zones when the voltage measurement decreases. If a shortage occurs in the low voltage capacitor bank, the measured voltage will drop, and may cause the distance protection logic to operate the relay as if a primary system fault were present.

4. Case Study

Simulations using the PSCAD/EMTDC platform have been carried out to reproduce the event described in Figure 7 and Figure 9. Figure 10 is an example of a detailed CCVT model. The model implements all of the five components, as discussed in Section 2. C1 and C2 are variable capacitors, of which the value depends on the number of workable capacitor stacks of the capacitor voltage divider, as shown in Figure 11. When a capacitor stack short-circuits, the value of the C1 or C2 will be recalculated. The burden is assumed to be 2000 Ohms.

PMU function in relays has been enabled in several AEP substations,to better monitor the performance and health of instrument transformers. In order to provide CCVT failure mode data to support the PMU measurement-based CCVT health monitoring algorithm as described in [9], simulated data is saved in COMTRADE file format.

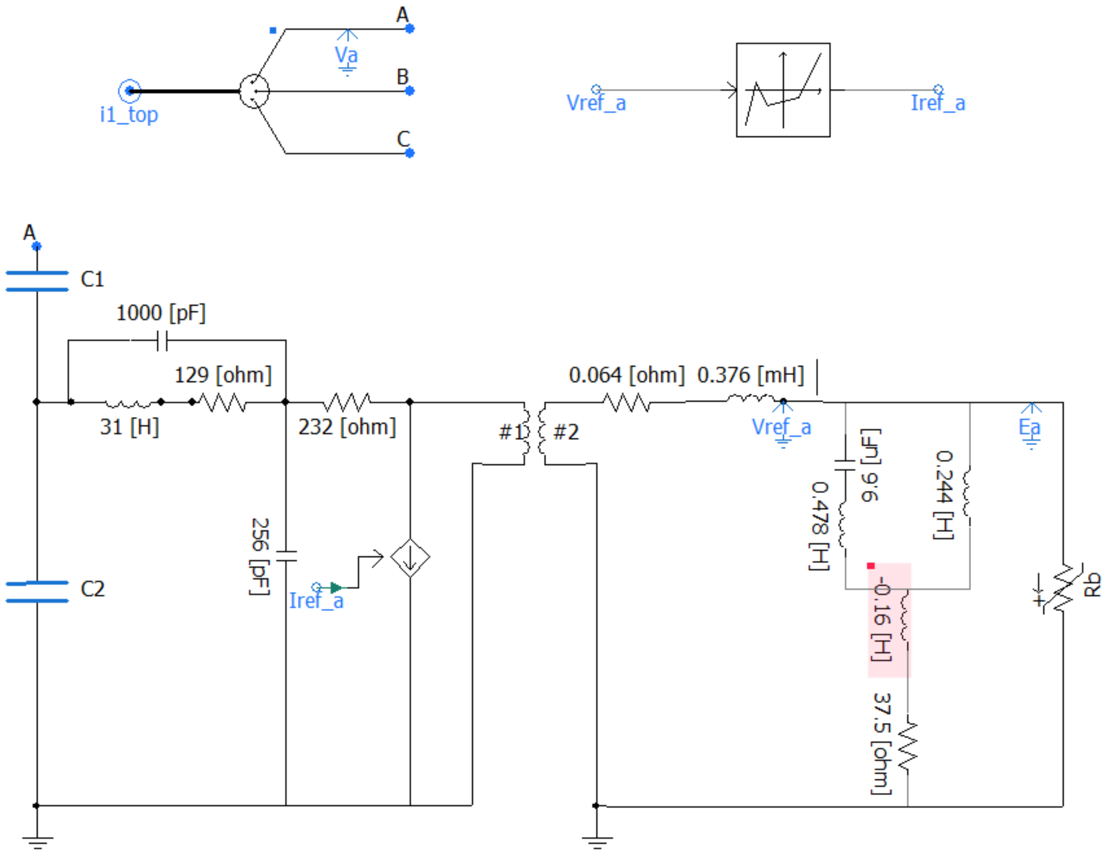

Figure 10 PSCAD model for a CCVT

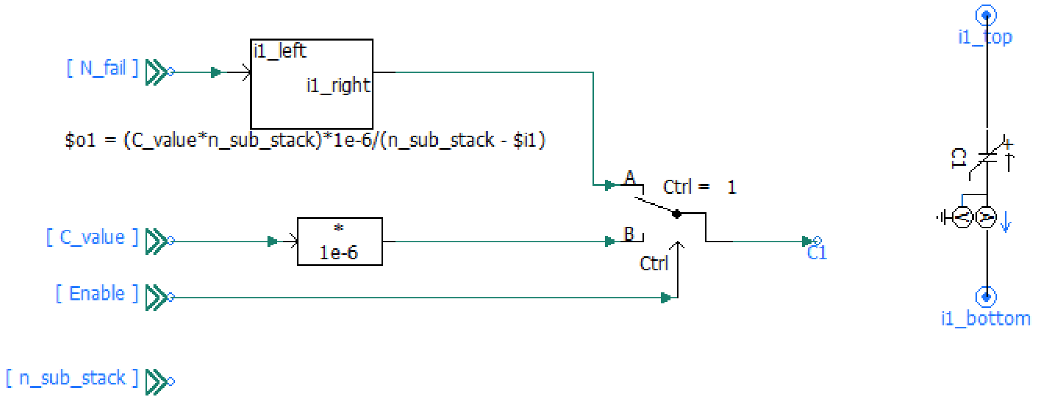

Figure 11 PSCAD model for C1 and C2

In the simulation representing a CCVT failure in Figure 7, we assume that the failed CCVT is installed on Phase B and that one capacitor stack was short-circuited every second. As shown in Figure 12, after six seconds, the measured voltage of Phase B goes above 1.05 p.u. while the measured voltage of Phase A and C remains at 1.0 p.u.

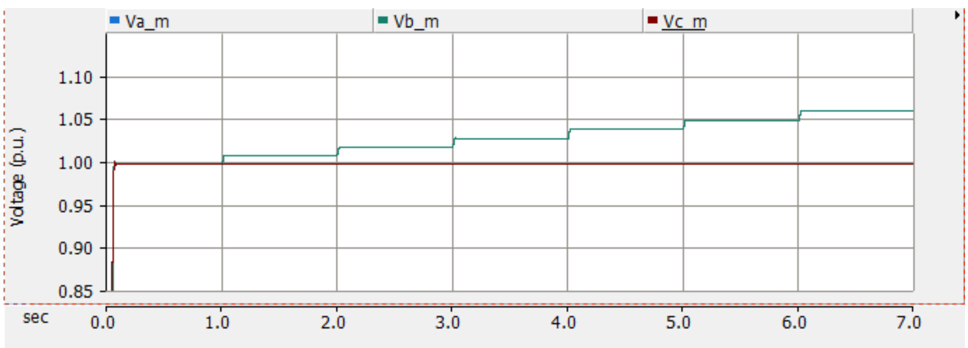

Figure 12 PSCAD simulation of successive capacitor stacks damage of C1

In the simulation representing the CCVT failure in Figure 9, we assume that the failed CCVT is installed on Phase C; two capacitor stacks were short-circuited at one second; and another three capacitor stacks were short-circuited at three seconds. As shown in Figure 13, after five capacitor stacks were damaged, the measured voltage of Phase C drops below 0.8 p.u., while the measured voltage of Phase A and B remains at 1.0 p.u.

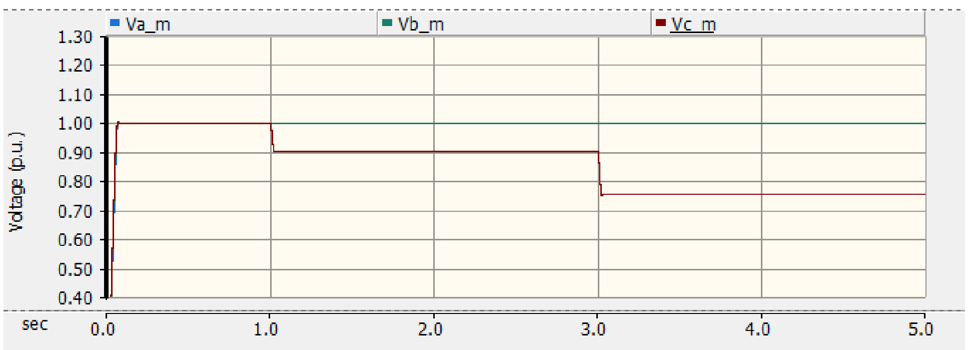

Figure 13 PSCAD simulation of successive capacitor stacks damage of C2

5. Conclusion

This paper proposed a detailed CCVT model to be used with PSCAD for transient study and investigation of CCVT failure modes. Improvements of existing models for each component of a CCVT are carefully designed to adapt the needs for CCVT failure mode simulation. Root causes of CCVT failure and impacts of CCVT failure on relay operation are presented. The time domain simulation of the CCVT failures show good agreement between simulated and recorded voltage profiles.

Generic CCVT failures are predictable. The proposed CCVT model can be used to predict the CCVT condition, given that the voltage profile and evaluate whether a repair or replacement is needed. The model can also be used to produce simulated training data for CCVT health monitoring programs, which are tuned to detect generic damages of CCVT, and to enable prompt removal of the device before a possible catastrophic failure or relay operation.

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