Transient Network Analysis of a 132kV Sub-transmission System Incorporating a Saturated Core Fault Current Limiter

S. M. Gunawardana, S. Perera and J. W. Moscrop

***Abstract*—A saturated core Fault Current Limiter (FCL) is a fault current reducing device that has attracted significant attention from both researchers and electricity utilities. This paper presents the potential performance of a saturated core FCL in a 132kV sub-transmission system, utilising a new comprehensive time-domain model to represent the FCL. PSCAD/EMTDC is used to perform the transient analysis and the behaviour of the saturated core FCL during normal steady state operation (un-faulted) as well as during a fault event is investigated, including the effects on voltage sags and Transient Recovery Voltage (TRV) of circuit breakers. The study results are compared to that of an equivalent air-core reactor, where the application of saturated core fault current limiters in transmission circuits is shown to have significant merit over the conventional current-limiting series reactors.**

***Index Terms*—Electromagnetic transients, fault current limiter (FCL), PSCAD, transient Recovery Voltage (TRV), voltage sag**

I. Introduction

THE continuous growth in the electricity demand, along with the perpetual expansion and reinforcement of interconnected high voltage electricity networks, have been noted to cause an increase in system fault current levels, which can exceed the maximum short-circuit ratings of existing switchgear. A Fault Current Limiter (FCL) is a device that is ideal for such locations in the grid where fault current levels are approaching or exceeding existing switchgear ratings.

Amongst the emerging fault current limiting technologies, saturated core FCLs are currently considered to be one of the most promising and have attracted significant attention from both researchers and electricity utilities. A number of different saturated core FCLs with distinct core topologies are currently being designed and tested [1], [2]. Computer-aided modelling and simulation are fundamental steps in demonstrating the benefits of this technology in network applications. In order to perform these network simulations, an accurate model of the FCL is required. However, accurately representing a saturated core FCL in transient network analysis software has always been difficult, due to the intricate magnetic characteristics of the device.

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In this paper, network simulation studies are undertaken in PSCAD/EMTDC transient simulation package to analyse the operational behaviour and performance of a saturated core FCL in a 132kV sub-transmission network. A new comprehensive time-domain model for the saturated core FCL is used to represent the FCL. The model is developed based on an analytical reluctance model proposed in [3] and couples the magnetic behaviour and the subsequent operation of the device to the electrical system. Unlike the preceding models proposed to elucidate the behaviour of saturated core FCLs, this time domain model accounts for the AC electrical circuit (i.e. AC coils and grid side network) to DC electrical circuit (i.e. biasing arrangement of the FCL) coupling effects and is far more accurate and comprehensive compared to the former models.

Both PSCAD/EMTDC and E-TRAN are employed to develop the 132kV network model, which is used to perform the transient analysis and to examine the behaviour of the saturated core FCL during normal steady state operation (un-faulted) as well during a fault event. The system studies also investigate the effect the saturated core FCL has on voltage sags during a fault event as well as the impact on Transient Recovery Voltage (TRV) of circuit breakers. The influence of the FCL on network power flow are also examined and compared with that of an equivalent air core reactor that provides the same current limiting as the FCL. It is demonstrated that the use of an equivalent air-core reactor could impose significant constraints on network power flow compared to the saturated core FCL with the same current limiting capabilities.

II. Saturated Core FCL Model Representation

A. Operating Principles

The basic operating principles of a saturated core type FCL are well documented in [4]–[7]. In essence, a saturated core FCL is a variable inductance iron core reactor, which is saturated under steady state un-faulted conditions and has an impedance similar to that of an air-core reactor. During a fault event the cores desaturate, resulting in an instant increase in impedance effectively limiting the fault current.

B. Time-Domain Model of the Saturated Core Fault Current Limiter

An equivalent electric circuit, derived based on the electromagnetic dual of the magnetic reluctance circuit proposed in [3], coupled with the AC (i.e. AC coils and grid side network) and DC (i.e. biasing arrangement of the FCL) external electrical circuits is used to represent the saturated core FCL in this paper.

The FCL model is implemented in PSCAD as a page module and inserted into the AC network using external electric nodes (A and B) as shown in Fig. 1. The ideal coupling transformers T1 and T2 represent the coupling between the equivalent electric circuit and the AC winding. The DC circuit, consisting of an external DC power supply energising the DC bias winding, is connected directly to the equivalent electric circuit.

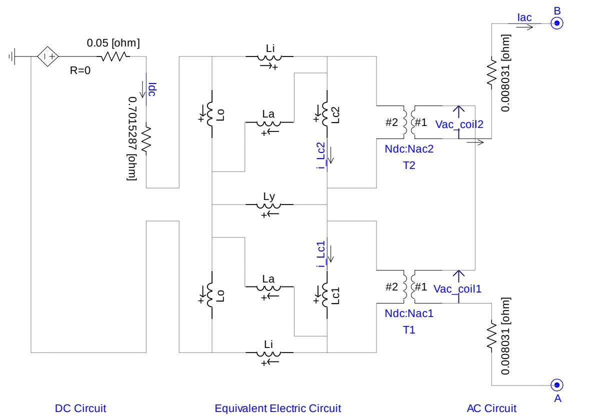


Fig. 1. PSCAD/EMTDC model of the FCL

III. Network Model Development and Validation

In the course of this study, two types of PSCAD/EMTDC network models were developed based on power system data of a real power network, provided by a transmission utility.

A detailed network model was developed based on original PSS/E data, including network segments at 330kV, 275kV, 132kV and 110kV voltage levels, for the frequency scan analysis and fault studies. E-TRAN was employed to generate the preliminary network model in PSCAD/EMTDC from the PSS/E raw data files provided by the utility. Frequency scans were carried out to identify the portion of the network to be directly translated into PSCAD/EMTDC and network equivalents were created to represent the remaining network by E-TRAN. Fig. 2 shows the frequency scans for different network equivalents, keeping the details of 2, 3, 4, 5, 6 and 7 buses away from the main point of interest (132kV Bus 2 at Substation A). As can be seen, at 7 buses away the frequency scan of the equivalent network is almost identical to the frequency scan at 6 buses away. Hence, it can be assumed that starting from 6 buses away, the equivalent network provides a good approximation for the whole network. The circuit was reduced to sub-pages according to the voltage levels and another sub-page was created with an equivalent of the rest of the network.

When performing a TRV study in EMT simulation, a detailed representation of the substation of interest is necessary. Therefore, a further detailed model of the Substation A was

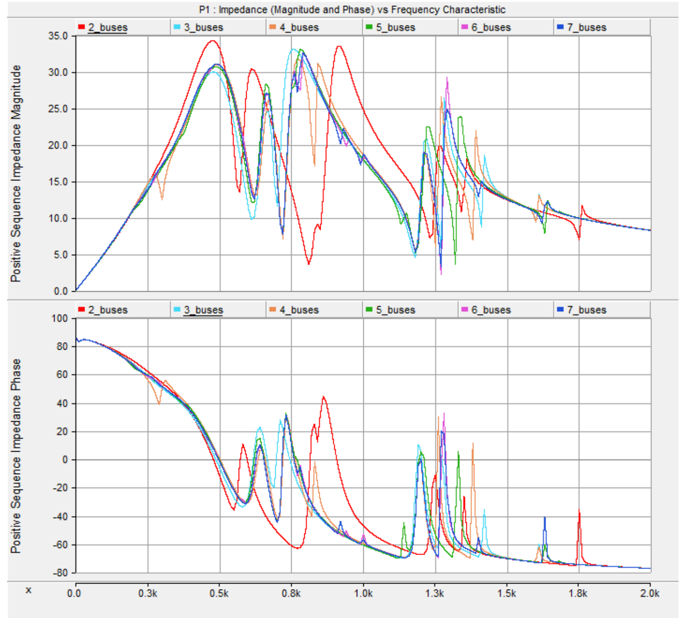


Fig. 2. Frequency scans at the 132kV Bus 2

developed as a page component (replacing the station equivalent generated by E-TRAN), using the E-TRAN generated transmission network model as the base case representing the system interconnection. This detailed substation model accounts for the effective stray capacitances and inductances of various substation equipment such as circuit breakers, disconnector switches, surge arrestors, transformers, bus VTs, series reactors etc. Where the capacitance values of station equipment were not available, the minimum recommended values in IEEE Standard C37.011-2011 [8] were adopted. Part of the detailed station model is illustrated in Fig 3.

The network model created was validated by performing a load flow study in PSCAD/EMTDC and comparing the results with those of an equivalent PSS/E load flow study. It was found that the results from PSCAD/EMTDC and PSS/E were in very good agreement, with the maximum difference being less than 1.32%.

IV. Application of Saturated Core FCL in 132kV Network

A. Saturated Core FCL Model Design and Implementation

The saturated core FCL design process involved the use of both Finite Element Analysis (FEA) and optimisation software to determine the optimal FCL design that would meet the performance specifications of the network under consideration. FEA simulations were used to analyse the flux distribution of the device and subsequently the reluctance of each flux path and the corresponding inductance values were determined.

The FCL designed was then modelled in PSCAD/EMTDC, using the parameters determined employing FEA, and the 132kV network was initially modelled as a simplified three-phase equivalent circuit to verify the limiting performance of the FCL. Table I summarises the model parameters including the values of the leakage inductance elements derived for

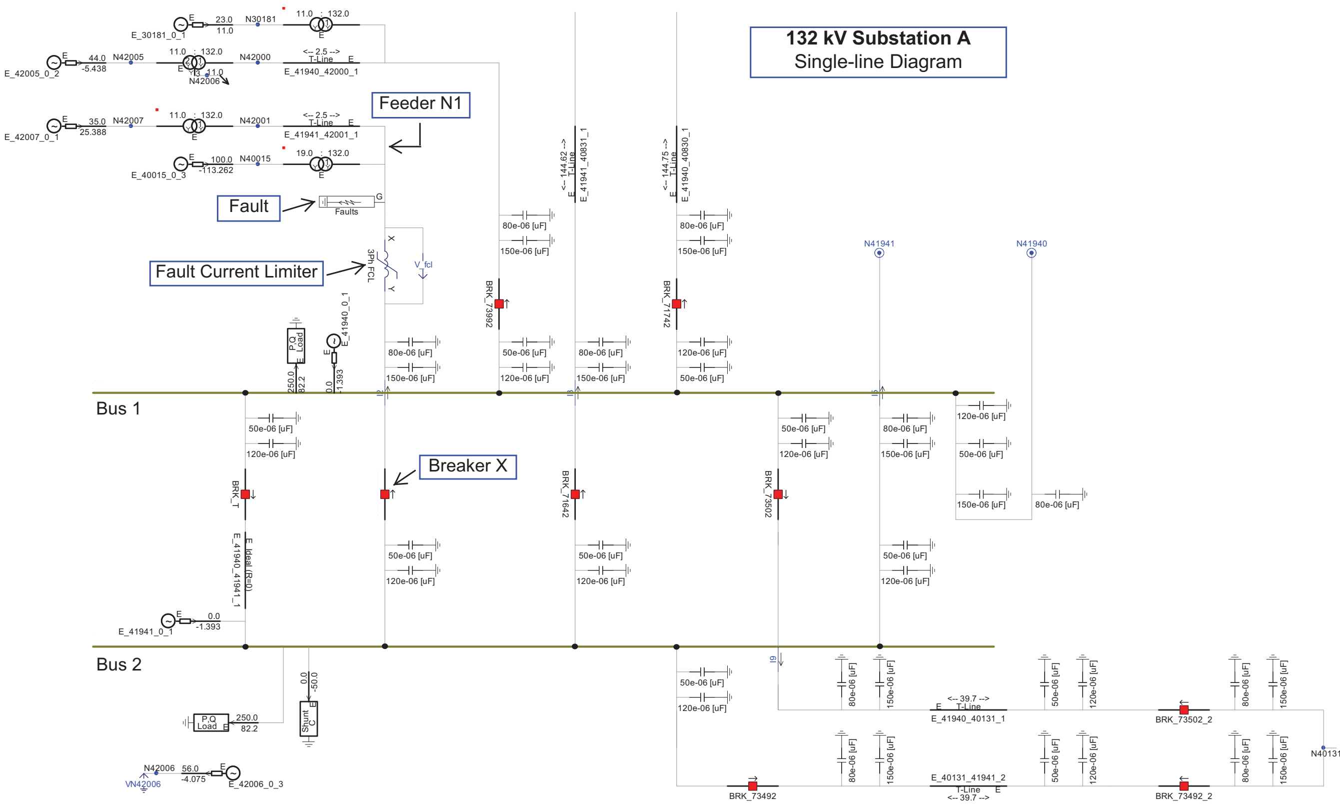


Fig. 3. Section of the detailed station model

this particular saturated core FCL device. The $L-i$ characteristic curve that was used to represent the non-linear core inductances L_{c1} and L_{c2} (indicated in Fig. 1) is illustrated in Fig. 4. Fig. 5a shows PSCAD/EMTDC simulated fault current with the simplified circuit compared to the FEA simulated fault current. Fig. 5b shows PSCAD/EMTDC simulated FCL terminal voltage with the simplified circuit compared to the FEA simulated FCL terminal voltage. As can be seen, the PSCAD/EMTDC generated waveforms replicate the FEA generated waveforms quite closely (providing a 46% reduction in symmetric fault current for a prospective symmetrical fault current of $41.66kA_{rms}$).

B. Network Simulations

The three-phase FCL model was inserted into one of the 132kV transmission incoming feeders (henceforth referred to as Feeder N1) of Substation A of the E-TRAN generated network as shown in Fig 3.

Table I
FCL MODEL PARAMETERS

Parameter	Test 1
AC voltage	132 kV
DC bias	143.39 kAT
Number of turns: AC coil	72
AC coil resistance	16.06 mΩ
Number of turns: DC coil	300
DC coil resistance	0.70 Ω
L_y [a]	353.12 H
L_a [a]	91.85 H
L_i [a]	16.13 mH
L_o [a]	18000 H

[a] Leakage inductance elements of the equivalent electric circuit as indicated in Fig. 1

V. PERFORMANCE OF THE SATURATED CORE FCL

A. Steady State Operation

Simulations were carried out in PSCAD to examine the performance of the FCL under normal steady state (unfaulted) conditions, focusing particularly on the steady state currents, voltage drop and the effects on active and reactive power flows in Feeder N1. The performance of the FCL was then compared with that of an equivalent air-core reactor, providing the same fault current limiting at the same network location. The inductance of the equivalent air-core reactor that would provide the same current limiting was calculated to be

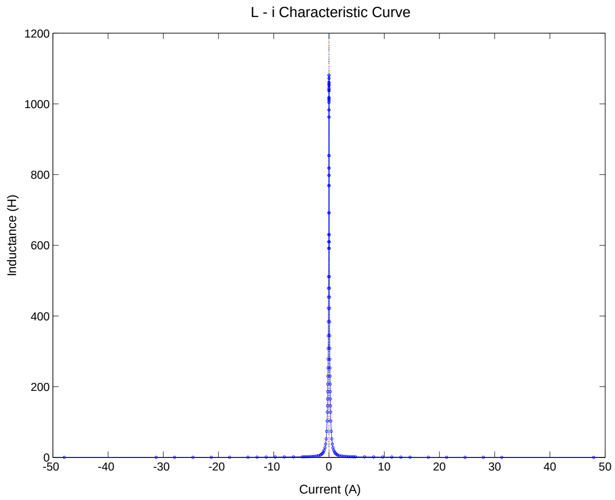
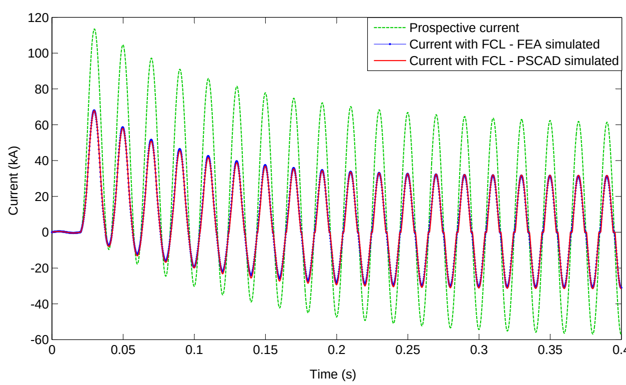
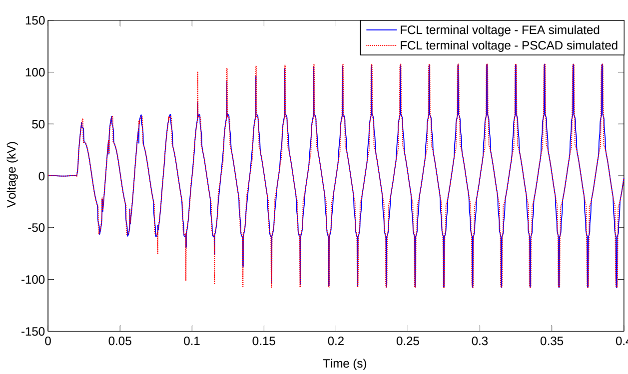


Fig. 4. Inductance - current characteristic curve representing the non-linear core inductances L_{c1} and L_{c2}



(a)



(b)

Fig. 5. FEA and PSCAD/EMTDC simulated (a) fault current [kA] (b) FCL terminal voltage [kV]

Table II
STEADY STATE PERFORMANCE COMPARISON

	Without FCL	With FCL	With equivalent air-core reactor ($6.0987mH$)
Steady state current (A_{rms}) [reduction]	687.6	662.38 [3.7%]	625.79 [9.0%]
Steady state voltage drop (V_{rms})	N/A	486 .89	1198.76
Active Power Flow (MW) [reduction]	134.10	129.1 [3.7%]	122.3 [8.8%]
Reactive Power Flow (MVAr) [reduction]	-93.45	-90.22 [3.5%]	-85.11 [8.9%]

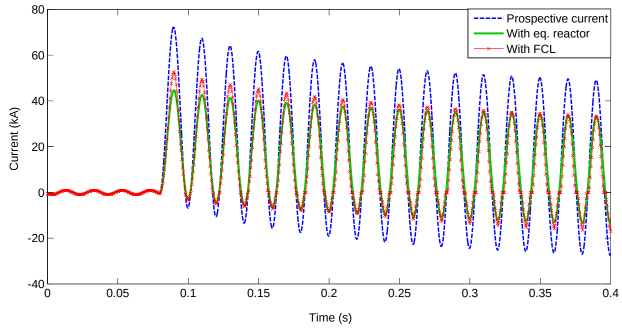
$6.0987mH$. A summary of the key results are presented in Table II.

As demonstrated in Table II, the equivalent air-core reactor has a much greater effect on the line currents and associated power flows compared to the FCL at the steady state. While the FCL causes a reduction, in the range of 3.5% to 3.7%, in the line currents and the active, reactive power flows, an air-core reactor with the same current limiting capability causes approximately 9% reduction in the line current and the associated power flows in the steady state. The pre-fault (steady state) voltage drop of the FCL is approximately $486.89V_{rms}$ (0.37%) compared to the $1198.76V_{rms}$ (0.91%) voltage drop of the equivalent reactor. It must be noted that in this particular network, the maximum allowable voltage drop across the current limiter, as specified by the utility, was 1.0% at rated line current - and the pre-fault voltage drop of the equivalent reactor at 0.91% is close to this maximum allowable value.

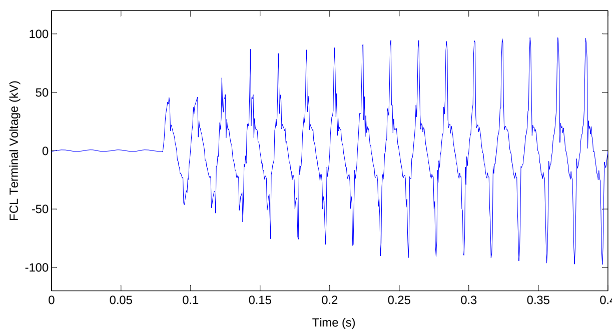
B. Limiting Behaviour in the Network

To examine the performance of the FCL under fault conditions EMT simulations were carried out, where a three-phase to ground fault was applied at 0.08s (at voltage zero, to obtain the maximum peak asymmetrical current). The fault was simulated adjacent to the FCL on the incoming feeder for a duration of about 10 cycles. To ensure network solution accuracy, a small solution time step of 5 µs was chosen and the switching events were interpolated to the precise time.

Fig 6(a) shows the resulting fault currents observed with and without the current limiting devices connected. As illustrated in Fig 6(a), the prospective unlimited peak fault current was limited by 30% with the FCL installed while the symmetrical fault current was limited by approximately 35%. The equivalent reactor of $6.0987mH$ was chosen to provide the same symmetrical fault current limiting as the FCL and thus, as can be seen from Fig 6(a), the current limiting provided by the FCL and the reactor are slightly different at the transient phase of the fault current, but are approximately the same during the steady state of the fault. Fig 6(b) shows the voltage across the FCL terminals during the fault event.

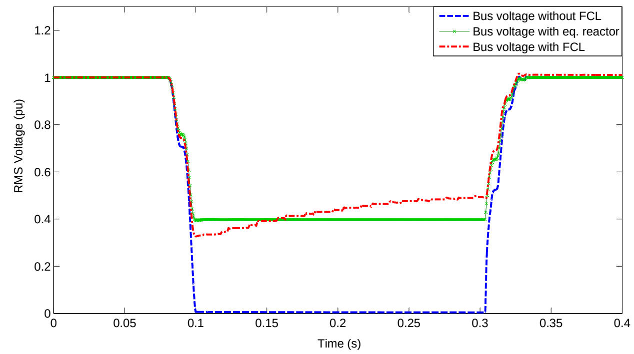


(a)



(b)

Fig. 6. Three-phase short-circuit fault applied at 0.08s (a) faulted line current [kA] (b) FCL terminal voltage [kV]



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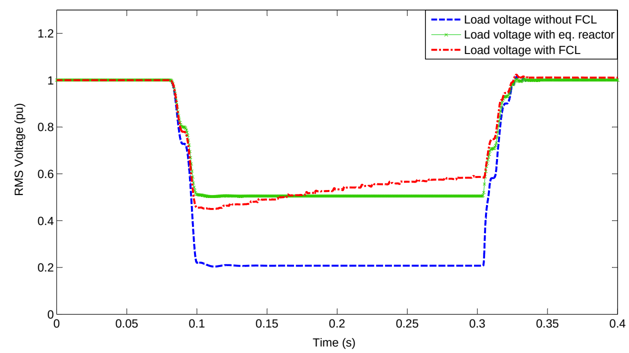

(b)

Fig. 7. RMS (one-cycle) voltage for the voltage sag (with 256 samples in a cycle) [pu] (a) experienced by Bus 2 (b) experienced by a remote load connected downstream from Bus 2

C. Effect on Voltage Sags

Transmission systems are generally tightly interconnected for reliable operation and their protection systems are designed to detect and isolate faults quickly, typically within 3-6 cycles. Hence, a fault on the transmission system, such as the one shown in Fig. 3, does not cause interruption at low voltage distribution levels. However, while the fault is on the transmission system, the entire system, including the distribution system, will experience a voltage sag. This can cause customer loads sensitive to supply voltage deviations, to drop out.

For the fault scenario discussed above, the bus voltages during the fault event with and without the FCL/equivalent reactor connected are illustrated in Fig 7a. In this case, the bus voltage shows a voltage sag during the fault, that will propagate to all the lines connected to the 132kV bus. For the same fault scenario, the voltage sag experienced by a remote load connected at 33kV voltage level is shown in Fig. 7b. As illustrated in Fig 7a, the saturated core FCL improves the voltage sag experienced by Bus 2 during the fault event by maintaining approximately 34% - 48% of the nominal voltage during the fault, thus allowing some of the loads connected to the bus to ride through the shallower sag.

D. Effect on Circuit Breaker Transient Recovery Voltage

The use of current limiting devices is known to have a favourable effect on circuit breakers by mitigating the interrupting burden imposed on them. However, the transient recovery voltage associated with circuit breakers while interrupting series reactor-limited short-circuit currents on transmission lines, has been reported to be severe [9]–[11]. Therefore when considering FCL applications, it is important to analyse the subsequent TRVs of relevant circuit breakers in the vicinity, to ensure that the TRV withstand capability of the associated circuit breaker is not exceeded.

According to IEEE Standard 37.011-1994 [9], the most severe recovery voltages tend to occur across the first pole that opens in a circuit breaker interrupting a symmetrical three phase ungrounded fault at its terminal when the system voltage is maximum. The TRV associated with asymmetrical current interruption has been found to be less severe than when interrupting a symmetrical current [9].

For this particular study, to evaluate the TRV performance of a 170kV, 40kA circuit breaker (referred to as Breaker X in Fig. 3), a symmetrical three-phase ungrounded fault occurring at the same location on the Feeder N1 as illustrated in Fig. 3 was considered. The Breaker X was simulated to interrupt the fault at the current zero crossing.

Fig. 8 illustrates the results of the TRV analysis of the Breaker X for the three scenarios: (a) without the presence of a current limiter, (b) with an equivalent series reactor (modelled as a lumped inductance with a parallel resistance added for realistic high frequency damping to avoid numerical integration instabilities [12]) and (c) with a saturated core FCL in the circuit. It also illustrates the maximum terminal fault TRV withstand capability of the breaker at 100% of its rated short-circuit current (T100) as defined by the IEEE Standard C37.06-2009 [13]. Note that for both the FCL-limited and series reactor-limited fault scenarios the associated circuit breaker is interrupting a reduced fault current ($17.7kA_{rms}$), that is approximately equal to 45% of its rated short-circuit current. Therefore, a TRV capability envelope for a 170kV breaker at 45% test duty (T45) was also derived by a method of interpolation [8].

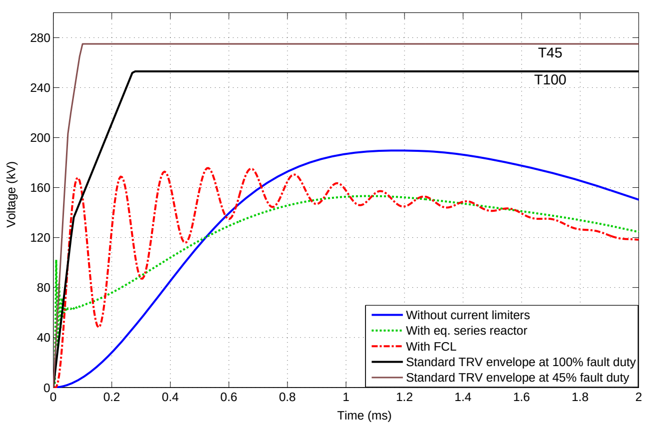

Fig. 8. First pole-to-clear TRV of a 170kV, 40kA circuit breaker interrupting a symmetrical three-phase ungrounded terminal fault [kV]

As demonstrated in Fig. 8, without the presence of a current limiter, the TRV of the circuit breaker is within the standard T100 TRV envelope. However, in both series reactor-limited and saturated core FCL-limited fault scenarios, the system TRVs exhibit lower peak magnitudes compared to the scenario with no current limiter, but with significantly higher rate-of-rise-of-recovery voltages (RRRV) (more severely in the case of series reactor-limited scenario). It must also be noted that high frequency oscillations can be observed in both FCL-limited and series reactor-limited TRVs, particularly at the very beginning of the waveform. Despite the higher RRRV and the high frequency oscillations, the system TRV resulting from interrupting the FCL-limited fault current is still within the standard-defined TRV capability at 45% fault duty. However, in the series-reactor limited scenario, the RRRV greatly exceeds the standard TRV capability. In cases such as this, [8] recommends adding a capacitance in parallel to the reactor to modify the RRRV to an acceptable level or using a definite purpose circuit breaker for fast transient recovery voltage rise times.

VI. Conclusions

The potential performance of a saturated core FCL in a 132kV sub-transmission system was analysed in this paper, utilising a new comprehensive time-domain model of the FCL. A potential FCL design that would meet the performance specifications of the network under consideration, was presented, and was shown to provide approximately 35% reduction in symmetrical fault current when inserted into the network.

The application of saturated core fault current limiters on transmission circuits was shown to have significant merit over the conventional current-limiting series reactors. This is particularly true when considering the performance of the FCL compared with that of an equivalent air-core reactor, under normal steady state (un-faulted) conditions. Significant performance differences between the two could be observed in terms of their respective effects on steady state current and network power flows. In comparison to the FCL, the equivalent air-core reactor imposes greater constraints on the network power flows and has considerably larger steady state voltage drop under pre-fault conditions.

It was also demonstrated that the saturated core FCL improves the voltage sag experienced both at the transmission and distribution voltage levels, for a transmission level fault. It was also shown that, despite the higher RRRV and the high frequency TRV imposed by the FCL-limited fault, the system TRV resulting from interrupting the FCL-limited fault current is still within the standard-defined TRV capability curve.

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