Analysis of Circuit Breaker Application Based on Transient Recovery Voltage Using Frequency Domain Techniques

D. Sinder, A. C. S. Lima, S. Carneiro Jr., A. C. Carvalho

***Abstract*—this paper addresses the problem of Transient Recovery Voltage (TRV) calculation with the specific purpose to assist in studies of circuit breaker overrating analysis. The TRV is associated with the so-called dielectric phase of the arc-interruption phenomena. System complexity, together with the large number of circuit breakers requiring this analysis, demand expedite methods, providing that acceptable accuracy can still be achieved. The aim of the proposed method of TRV calculation is to identify, from the large number of circuit breakers requiring such analysis, the ones which really need detailed TRV evaluation. A brief review of TRV calculation is presented and a new method is proposed based on Frequency Domain using the Fast Fourier Transform.**

***Keywords*: TRV, equipment overrating, Frequency Domain, FFT.**

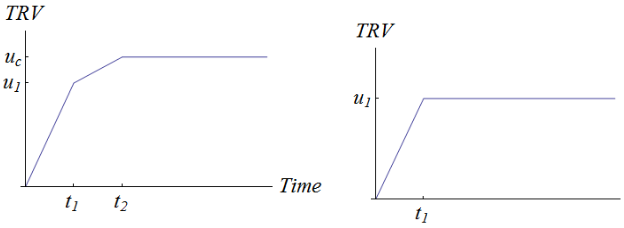
I. INTRODUCTION

THE overrating of high voltage circuit breakers (CBs) is an ever growing problem as power systems throughout the world tend to be increasingly connected. The symmetrical and asymmetrical short-circuit currents, the load currents and the transient recovery voltage (TRV) are amongst the most important parameters for the analysis of CB overrating. TRV calculation can be laborious and time consuming, usually demanding EMT-type studies [1]-[3].

The evaluation of CB overrating is normally carried out in two steps. The first step consists on the identification of those CBs that are prone to become overrated due to new stations and/or transmission lines connected to the system. The second step consists on a more detailed analysis of such CBs, including the load current, symmetrical and asymmetrical short-circuit currents, peak short-circuit current and TRV. This paper is concerned with TRV evaluation, and for space reasons will not discuss any of the other aspects of CB overrating.

The TRV is associated with the so-called dielectric phase of the arc-interruption phenomena. During this phase, the arc conductivity decreases as the instantaneous current approaches zero. Immediately after the current becomes zero, the arc column will be subjected to the voltage across the moving CB contacts. At this time, the withstand voltage of the CB is gradually restored as the distance between the contacts increases. The instantaneous voltage across the contacts is the TRV and if this voltage surpasses the dielectric supportability of the arc column, arc re-ignition may occur and the CB operation will fail [4], [5]. In summary the study determines the capacity of the CB for arc extinction under stresses imposed by the rate of rise and peak values of TRV.

The Standard IEEE C37.011-2005 [6] specifies that the TRV curve should be compared with an envelope based on four parameters, as shown in Fig 1(a), which is deemed adequate for nominal voltages above 100kV. For lower voltages, a simpler form based on two parameters only, as shown in Fig 1(b), can be applied.



(a) Four parameters (b) Two parameters

Fig. 1. TRV envelopes

The CB is considered over-rated if the time-domain response crosses the envelope. Thus both the Peak Value and the Rate of Rise of Transient Recovery Voltage (RRTRV) should be analyzed. The above mentioned standard [6] proposes a simplified method for TRV calculation, which will be briefly reviewed in this paper and compared to a more rigorous approach using Electromagnetic Transients Programs.

Sinder [7] has indicated that the procedure described in [6] may lead to considerable differences in TRV values, at least for the kind of EHV Transmission Systems that were examined in the course of his work. Therefore the authors decided to propose an Inverse Fourier Transform (IFFT) approach for TRV calculation. The method is similar to that proposed by Steurer et al. [3], except that in the present case the frequency response of the network as seen from the CB terminals is calculated.

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This approach avoids an important simplification adopted in [3], which consisted in considering a triangular-shaped injected current to compute TRV, including the frequency response of transformers.

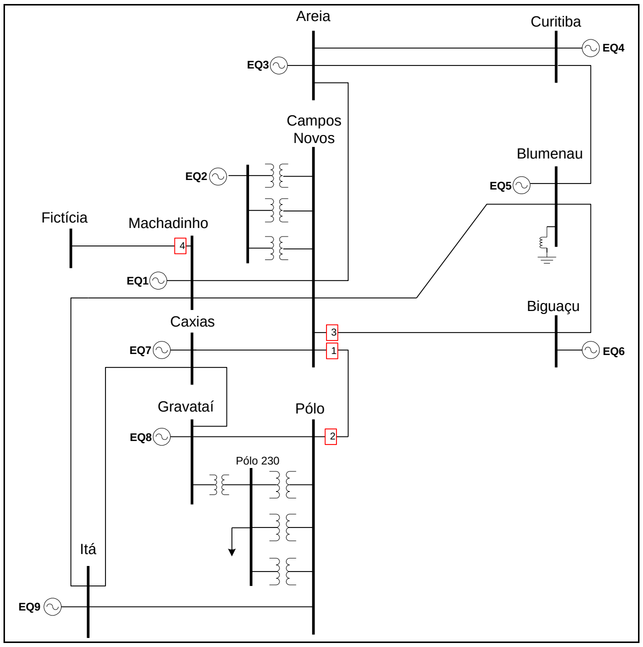

Fig.2 525 kV test system

II. COMPARISON OF TRV CALCULATION USING ATP AND IEEE STD C37.011-2005

The basic equations for TRV calculations proposed in [3] are shown in Appendix I. These equations were programmed and were used to compute the TRVs in CBs 1, 2, and 3 of the Test System shown below, considering three-phase grounded faults. The test system is part of the Southern Brazilian grid, where 15 transmission lines (total length approximately 2,800 km), six 525/230 kV transformers and other equipment, such as shunt reactors, were represented. This system was also implemented using ATP for comparison purposes.

The results are shown in Figs 3 to 5. The label IEEE stands for the results using IEEE Std. C37.011-2005. It is seen the RRTRVs are similar in the initial instants but considerable differences are shown as time progresses. One possible reason for such discrepancies can be attributed to the simplified modeling adopted in [6], there included the assumption that the transmission lines connected to the CB busbars do not contribute to the fault current. This assumption is implicit in (3) and (5) in the Appendix, as the short-circuit current is injected into the equivalent reactance computed from the connected transformers, sources and the transmission lines are represented by their positive-sequence surge impedances.

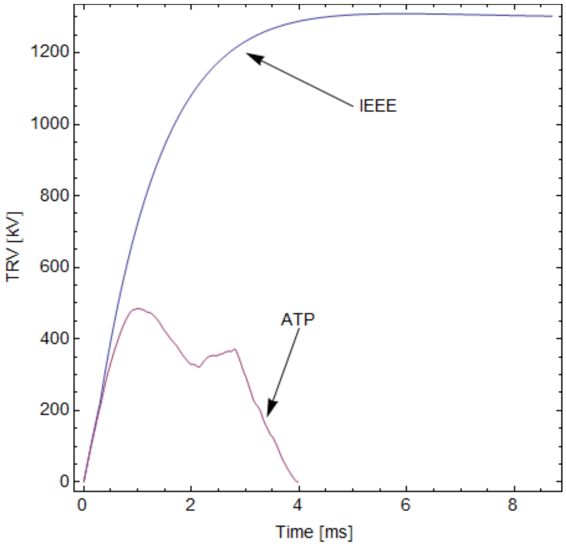

Fig. 3 TRV for CB 1 (Line—Campos Novos – Pólo)

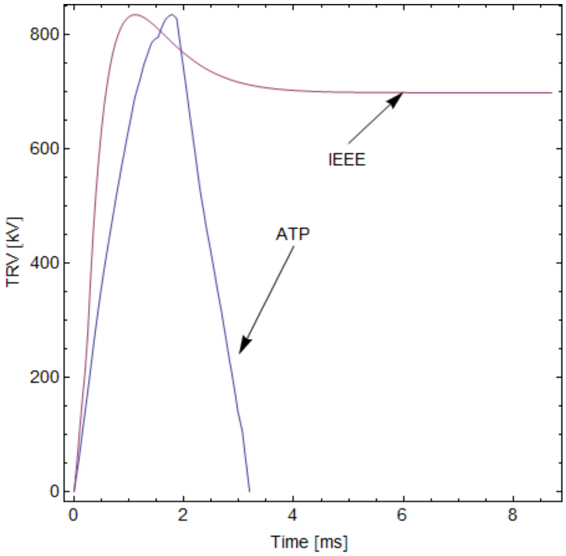

Fig. 4 TRV for CB 2 (Line—Pólo – Campos Novos)

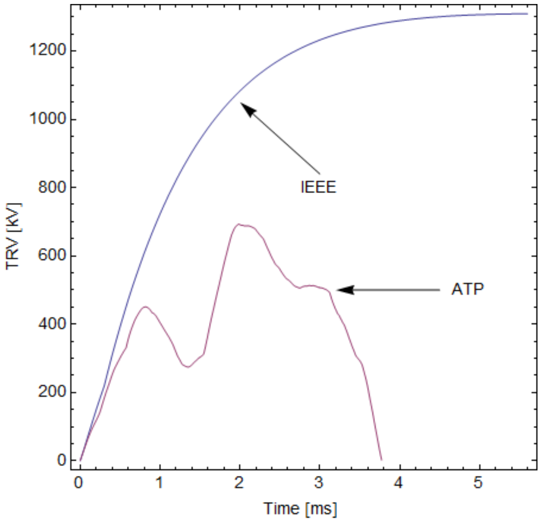

Fig. 5 TRV for CB 3 (Line—Campos Novos – Biguaçu)

It is well-known that in systems such as the Southern Brazilian being considered in this study, often the contributions from transmission lines to the short-circuit currents can be higher than those arising from the transformers. It may be concluded from the above observations that the simplified method proposed in [6] will presumably provide more reliable results when applied to distribution systems, as the feeders are usually not very long and are normally connected to loads.

III. TRV FREQUENCY DOMAIN CALCULATION

The proposed methodology is a time-frequency approach in which the TRV is first computed in the frequency domain, where the short-circuit current flows through the impedance “seen” by the CB terminals. This impedance represents the frequency-response Z(ω) of the entire network and could theoretically be obtained as the impulse response of the network.

After Z(ω) is obtained, the TRV could be calculated in the time domain by convolution with the frequency domain representation of the short-circuit current. This would correspond to the classical approach. In practice, Z(ω) can be calculated using available routines that have been developed for harmonic studies. These routines have been designed to determine Z(ω) at given discrete frequency values, over a suitable frequency range. In the proposed approach, the time-consuming convolution is avoided by obtaining the TRV directly in the discrete frequency-domain by simply multiplying the corresponding frequency components of the short-circuit current and Z(ω). An Inverse Discrete Fourier Transform can then efficiently compute the time-domain TRV.

In transient analysis of power systems, the FFT has been used with a complex frequency sampling. This procedure has been known as the Numerical Laplace Transform (NLT) or Modified Fourier Transform (MFT) [10-14]. However, the proposed methodology here relies on either impedance measurements or on the output of EMT programs, thus a real frequency is mandatory. This precludes the usage of NLT and the frequency responses will present a higher oscillatory behavior due to the poles near the imaginary axes. Fortunately the goal here is to analyze the first instants of the TRV, thus this limited time frame implies in a very narrow frequency bandwidth, allowing FFT usage without loss of accuracy.

A. *Short-circuit current*

It is well-known that the dielectric stresses imposed within a CB are higher when symmetric short-circuit currents are to be interrupted. Thus, neglecting the current asymmetry will lead to conservative TRV values [1], [2], [4-5]. Moreover, since the maximum TRV value occurs before the first current-wave peak, computation can be made using the first current half-cycle only. In order to prevent the spurious appearance of high-frequency harmonics after the TRV peak value is reached, the current is represented using the semi-sine function given by (1).

$$f(x) = \frac{1}{2}[1 + \sin(\omega t + T/4)] \quad (1)$$

A. *Fast Fourier Transform*

Frequency domain analysis has been applied to Power System transients studies since the early 1960’s. Traditionally, the series approximation has been used to calculate the time-frequency conversion. Unfortunately, this series presents very slow convergence properties and a large number of terms are needed. The development of the Fast Fourier Transform (FFT) in the mid 1970’s has overcome this issue. The FFT of a sampled function x(k) is given by (2).

$$X(k+1) = \sum_{n=0}^{N-1} x(n+1) e^{-i\left(2\frac{\pi}{N}\right)kn} \quad (2)$$

For an efficient application of FFT, an even number of time or frequency samples is preferred. For transient analysis a number of samples of 1024 suffice for most cases.

The main limitations are the Gibbs phenomenon and frequency aliasing. The Gibbs phenomenon involves “overshoots” that occur in replacing a given function by the partial sums of its Fourier series. It is however L_2-convergent, which means that the integral of the squared differences of the approximation to the given function goes to zero, but in general no pointwise convergence to the original function is achieved. This problem can be minimized by a windowing function such as the Lanczos, Hamming or Hanning windows [10]-[12].

Aliasing can be minimized by a smoothing function. For an effective implementation of an anti-alias filter, it is recommended to use a complex frequency. In the present study, the frequency domain samples are obtained at regular spans and using real rather than complex frequencies. For TRV calculation it was found that the aliasing errors could be minimized using a large number of samples (4096) and a total simulation time of 8/60 seconds. An alternative to the FFT is to apply the Spline Fourier Transform or the interpolated Fourier Transform [14-15]. The main advantage of these methods is to avoid equidistant frequency samplings.

IV. VALIDATION

The proposed methodology has been validated using the frequency-scan facility of the ATP to obtain the discrete values of Z(ω) corresponding to the CB terminals that were examined in Section II, Fig 3. The short-circuit currents were estimated using a standard fault calculation routine, and the methodology was implemented using MATLAB®, using a personal computer with Intel® Core™2Duo CPU E6550 @ 2.33GHz, 3,23 GB RAM, Microsoft Windows XP operational system.

The results were then compared with the ATP calculations. Figures 6 to 8 show some selected results and it is seen that close correspondence has been achieved.

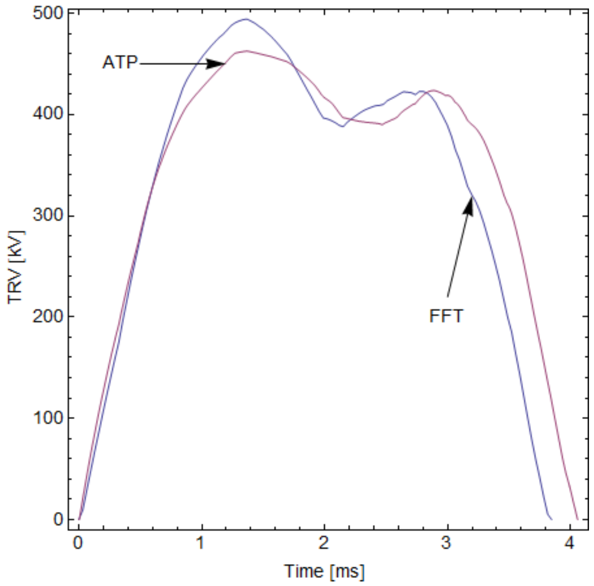

Fig. 6 Comparison of TRV for CB 1 (Line—Campos Novos – Biguaçu)

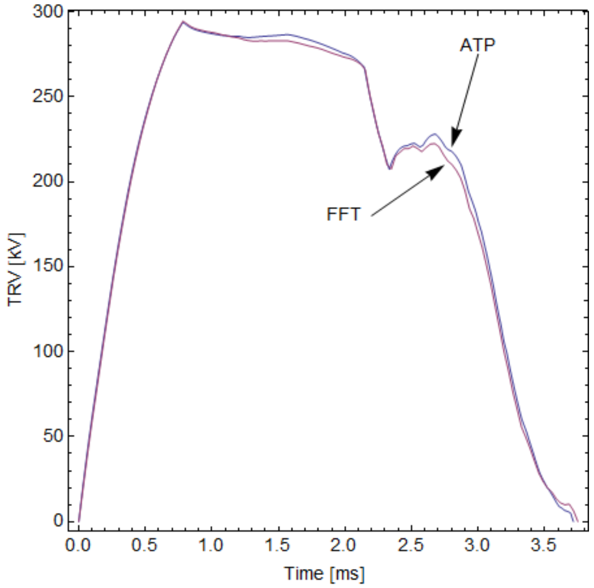

Fig. 7 Comparison of TRV for CB 1 (Line—Pólos – Campos Novos)

V. CONCLUSIONS

This work presents an expedite method to the assessment of circuit breakers in Power Systems. It uses the frequency response of the TRV across the circuit breaker terminals. The proposed methodology can be applied to large systems as it relies on the frequency dependent network equivalent seen from the breaker terminals. The time-domain responses are obtained using a Inverse Fourier Transform based on the FFT approach (IFFT). A large number of samples was used to avoid aliasing.

A test system based on an actual power system in Brazil was used to assess the performance of the proposed methodology. The TRVs were also calculated using ATP for comparison. The results have confirmed the validity of the proposed approach.

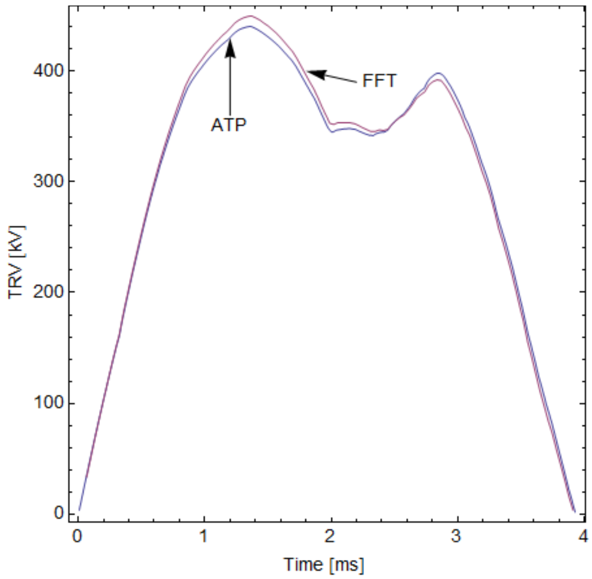

Fig. 8 Comparison of TRV for CB 3 (Line—Pólos – Campos Novos)

The ATP time-domain results were compared with the values obtained using Std C37.011-2005[6] and considerable differences were found. This indicates a need for further investigations, regarding the type of system to which the simplified methods proposed in [6] can be applied.

VI. APPENDIX

The method described in [IEEE Std C37.022-2005] is based on a simplified equivalent circuit analysis and applies the superposition principle. Since travelling wave phenomena is not considered, the method is only valid for the period of time up to the arrival of reflected surge waves at the point of analysis.

For the sake of clarity the main equations that are used to compute the cases of over and under-damped responses are given below for over-damped TRV

$$v(t) = \frac{3\sqrt{2}}{2} I\omega \mathrm{L} \left[1 - \mathrm{e}^{-\alpha t}\left(\cosh(\beta t) + \frac{\alpha}{\beta}\sinh(\beta t)\right)\right] \quad (3)$$

where I is the short-circuit in kA, ω is angular frequency, α=1/(2 Zeq C),

$$\beta = \sqrt{\alpha^2 - \frac{1}{LC}} \quad (4)$$

and Zeq is the equivalent impedance seen from the breaker terminals, L is the total equivalent inductance and C is the total phase to ground capacitance.

The approximate expression for the under-damped oscillations TRV is given by (5).

$$v(t) = \frac{3\sqrt{2}}{2} I\omega \mathrm{L} \left[1 - \cos\frac{\mathrm{t}}{\sqrt{\mathrm{LC}}}\right] \quad (5)$$

VII. REFERENCES

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