Detection of Fault Induced Transients in E.H.V. Transmission Lines for the Development of a Fault Locator System

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Abstract – **It is well known that typical voltage transducers utilized on E.H.V. power transmission lines have a limited bandwidth and that the frequency of traveling wave components of the fault induced transients is inversely proportional to fault distance along the lines. Frequencies to be expected can range from hundreds of Hz to infinite (for close in faults). It is shown that Coupling Capacitor Voltage Transformer (CCVT) secondary voltages, normally applied to conventional protection schemes, do not comprise the appropriate information for a scheme that operates on the high frequency fault generated transients. Regarding its secondary voltages, the CCVT acts as a low-pass filter, which rejects higher frequencies. Conversely, it is shown that it is possible to capture the appropriate traveling wave information (contained in the fault induced transients) using a high frequency tap from a CCVT. This tap acts as a high-pass filter, which rejects lower frequencies. This paper presents a number of ATP fault simulations studies on a typical 500 kV system.**

Keywords – Coupling Capacitor Voltage Transformer, Digital Simulation, High Frequency Tap, CCVT Digital Model, Frequency Response, ATP.

I. INTRODUCTION

The correct location of faults on E.H.V. power transmission lines is important to allow quick maintenance action of the repair crews. The Brazilian system is characterized by hydroelectric power plants separated from the consumer centers by long transmission lines. Its future growth is being planned to occur towards the north of the country, and this will require more long transmission lines. The studies presented in this paper are part of a broader work aiming at the study of a traveling wave fault locator scheme, which can be applied in the Brazilian E.H.V. transmission system.

In the development and utilization of high-speed protective relays or, as it is the interest in this study, of a traveling wave fault locator system for transmission line maintenance purposes, the transient response of Coupling Capacitor Voltage Transformer (CCVT), from which the voltage information is drawn, should be considered. This is particularly important if the relays or the fault locator system work on the high-frequency fault generated transients, rather than 60 Hz quantities.

Many researchers have developed sophisticated traveling wave algorithms [1,2]. In order to exploit the advantages of such schemes it is necessary to employ voltage transducers of sufficient bandwidth to allow accurate detection of the fast-rising waveforms associated with traveling waves. Although such transducers may be available from industry, in the Brazilian system all existing voltage transducers are designed with 60 Hz in mind.

It is the purpose of this paper to show, by means of digital simulation conducted with the Alternative Transients Program (ATP) [3], that Coupling Capacitor Voltage Transformer (CCVT) secondary voltages, normally applied to conventional relays and meters, do not comprise the appropriate information for a scheme that operates on the high frequency fault generated transients. Regarding its secondary voltages, the CCVT acts as a low-pass filter.

Also by means of ATP digital simulation, this paper shows that it is possible to capture the appropriate traveling wave information (contained in the fault induced transients) using a high frequency tap from a CCVT. This tap acts as a high-pass filter, which rejects lower frequencies. The idea to couple power line fault transients via the Power Line Carrier (PLC) tap of a CCVT is not new. It has been proposed in a pioneering work of Bonneville Power Administration (BPA) and dates back to the 1940's and 50's [4]. More recently this system has been brought up to date, as described by Street [5]. This paper contribution, in this aspect, for an application in the Brazilian system, comes from the fact that the effectiveness of the high frequency tap method of capturing the fault transients (and the theory supporting it) is corroborated via ATP simulations.

II. FAULT INDUCED TRANSIENTS

When a flashover occurs on a transmission line, a surge voltage generated at the fault point travels along the line towards its terminals, and multiple reflections will take place, giving rise to waves traveling back and forth on the line. Thus, the 60 Hz signal will appear corrupted by the presence of noise in the form of frequencies above 60 Hz. The dominant frequency of oscillation of fault induced transients depends on many factors such as line length, source impedance, fault location along the line, etc. [6]. A complete theory on fault induced transients, appearing at the line terminals, is presented by Swift [7]. A short and resumed description follows, just as a basis for helping the reader to understand the scope of this paper [7,8]. Consider the single-phase line of Fig. 1. The transmission line is unloaded before the fault and is short enough that the voltages at “A” and “B” are in phase with e_s. The fault switch closes at a peak of the sinusoidal voltage.

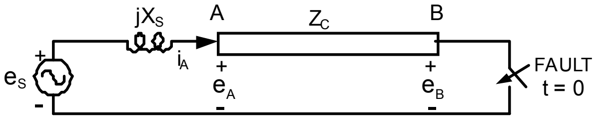

Fig. 1 Single-phase transmission line

When the source impedance Xs is small (strong source), the traveling waves generated by the fault are reflected with a negative sign at both ends of the transmission line and it takes twice the travel time for the wave to arrive at terminal “A” with the same sign. The dominant frequency of oscillation is thus [7,8]:

$$f = \frac{1}{2*\tau} \quad \text{and} \quad \tau = \frac{l}{v} \tag{1}$$

$$f = \frac{v}{2*l} \tag{2}$$

Where:

f = frequency of oscillation (Hz);
τ = travel time in seconds;
v = speed of travel in kilometers/second;
l = length of line in kilometers.

When the source impedance Xs is large (weak source) the traveling waves arriving at terminal “A” are reflected back with the same sign and at terminal “B” are reflected with opposite sign. One can conclude that a wave arrives twice at terminal “A” with the same sign every four travel times. The dominant frequency of oscillation is thus [7,8]:

$$f = \frac{1}{4*\tau} \quad \text{and} \quad \tau = \frac{l}{v} \tag{3}$$

$$f = \frac{v}{4*l} \tag{4}$$

On a three-phase line surges travel in, at least, two distinct modes: a phase mode and a ground mode. This means that each introduces a different frequency. Since the phase mode is faster, it introduces a higher frequency transient. In a real E.H.V. system, source impedance will be between the small (strong source) and large (weak source) limits. The dominant frequency of fault induced transients will be between the limits obtained with equations (2) and (4).

III. SIMULATED SYSTEM IN ATP STUDIES

The typical 500 kV system shown in Fig. 2 is used for the study with ATP. Frequency dependent parameters of the line were obtained by using JMARTI routine of ATP and the earth resistivity considered was 1000Ω.m.

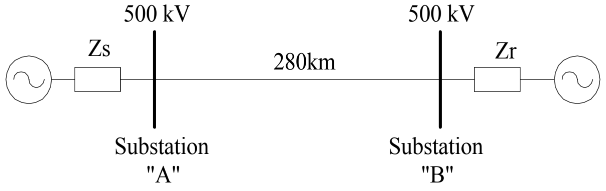

Fig. 2 One line diagram of the simulated system

Details of the transmission line tower construction are given bellow and in Fig. 3 and Table I [9].

- 500 kV compact tower;
- Phase conductors: 4 x rail 954 MCM 45/7;
- Shield wires: 3/8” EHS and OPGW (21 $kA^2.s$);
- Shield wires protection angle: 8^o

Table I Tower conductors spacing

Distance (m)	Phase a	Phase b	Phase b	Shield wires
Horizontal	-4.5	0.0	4.5	±3.17
Vertical	29.77	33.77	29.77	39.07

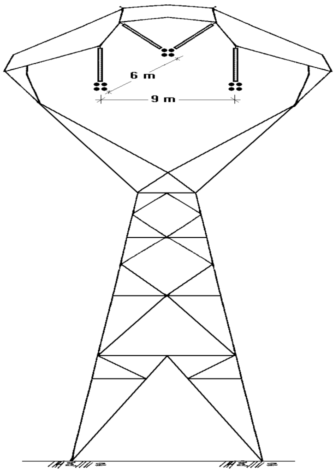

Fig. 3 500 kV transmission line tower configuration

A variety of transmission line fault situations were simulated with ATP. Fault types, fault locations and fault inception angles, in a real power system, are random in nature. In this aspect, the complete study done by authors covered a number of different situations. Source impedances were also varied. In this paper, due to the reduced six pages format, examples will be given for phase to ground faults applied at voltage peak. In the next section, the voltage waveshapes are computed for about 2.8ms prior to the fault, and a little more than one cycle after the fault (20ms total). A Fourier analysis is done after with GTPPLOT [10], to find the frequency content of the voltage waveshapes.

IV. FAULT SIMULATION AND SPECTRUM ANALYSIS

Results presented in this section are relative to primary voltage measurements in phase b (faulted phase at various points along the line) in terminal “A”. Fig. 4, 6 and 8 typify the results for phase-to-ground faults applied at a distance of 20, 70 and 210 km from terminal “A”, respectively. Fig. 5, 7 and 9 show the Fourier analysis for the above voltages (fundamental frequency is 60 Hz). It can be seen from the results that the frequencies of the dominant transient vary with the fault distance from “A”, and are, approximately, 3600, 1320 Hz and 540 Hz, respectively.

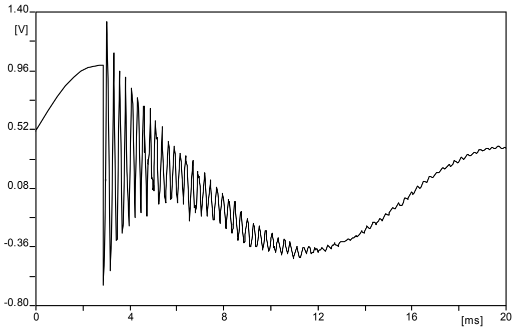

Fig. 4 Phase b primary voltage (p.u.), fault 20 km from “A”

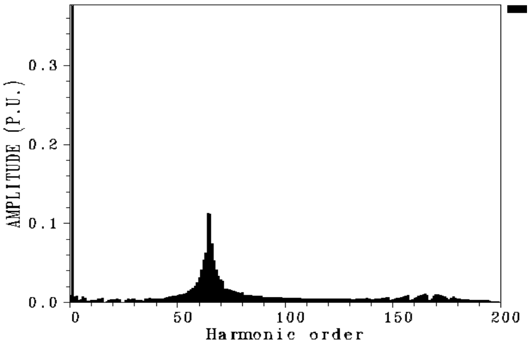

Fig. 5 Frequency spectrum of voltage in Fig. 4

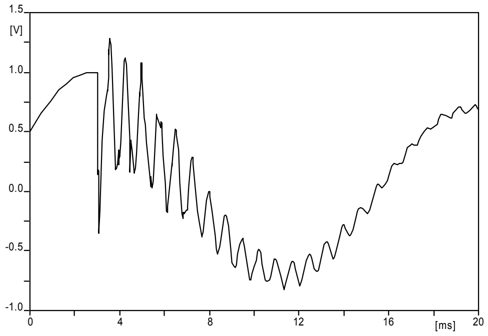

Fig. 6 Phase b primary voltage (p.u.), fault 70 km from “A”

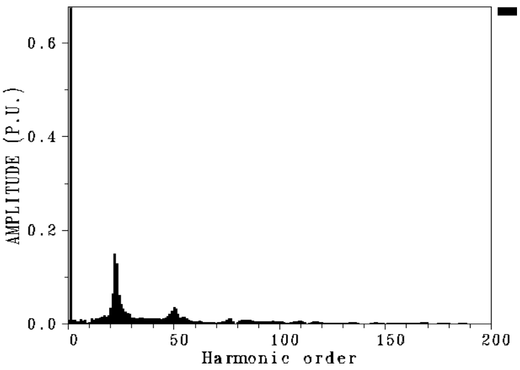

Fig. 7 Frequency spectrum of voltage in Fig. 6

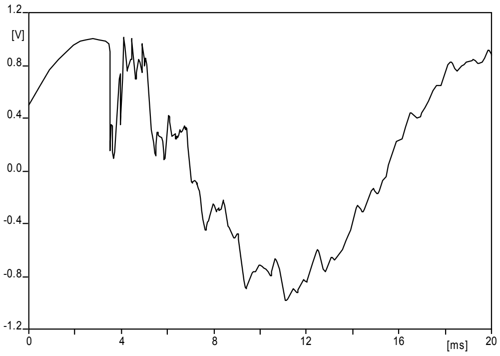

Fig. 8 Phase b primary voltage (p.u.), fault 210 km from “A”

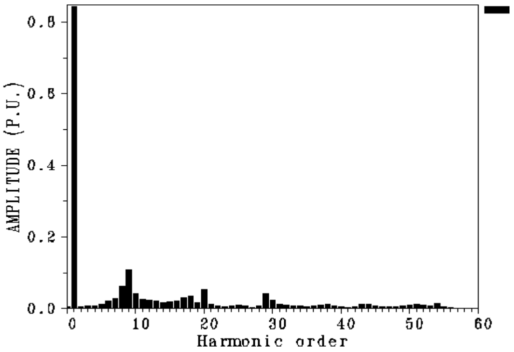

Fig. 9 Frequency spectrum of voltage in Fig. 8

V. CCVT SIMULATION IN ATP STUDIES

CCVT’s are widely used in the Brazilian E.H.V. system. They transform the E.H.V. line primary voltage to a designated low secondary voltage, usually 115 V line to line or 66.40 V line-to-neutral. In 60 Hz, the voltage finally available to feed relays and meters should be an exact replica of the primary voltage. The standard construction of a CCVT is shown in Fig. 10. In this circuit, capacitors C_1 and C_2 act as a potential divider for the primary voltage. The voltage across C_2 is fed via the compensating inductor L_c to a step-down transformer (SDT). The design also incorporates a ferroresonance suppression circuit (FSC) and, in some applications, a drain coil (L_d), for PLC connection.

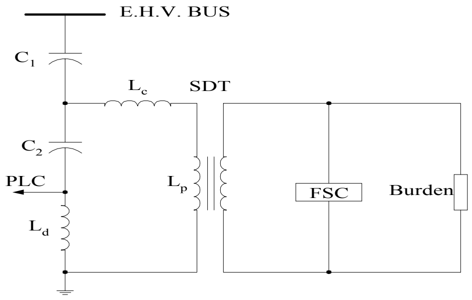

Fig. 10 Standard schematic diagram of a CCVT

In order to study the transient response of the CCVT, a detailed digital model (similar to an EPRI development of CCVT models intended for digital simulation of fault transients [8]) was added to the power system of Fig. 2. Succinctly, Fig. 11 shows the model included in the ATP simulations. More details can be seen in [8,11].

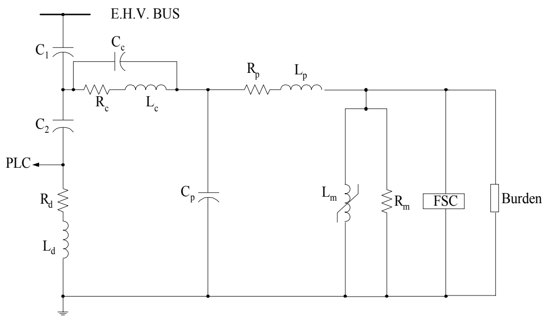

Fig. 11 – Typical CCVT digital model for ATP simulation

The frequency response of the CCVT model included in the simulations, obtained with the routine Frequency Scan of ATP, and plotted with MATLAB [12], is shown in Fig. 12. It can be seen that the frequency response is adequate up to, approximately, less than 1000 Hz, justifying the "low-pass filter action" of the CCVT.

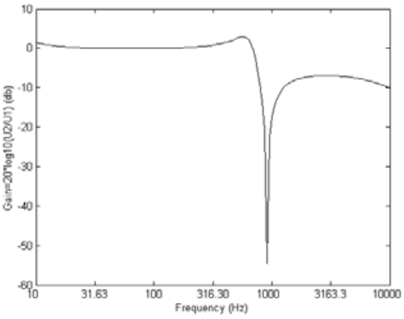

Fig. 12 – Frequency response of the CCVT digital model

VI. TRANSIENT RESPONSE OF CCVT

CCVT lose some fidelity when reproducing primary voltage transient variations because of inductive, capacitive and non-linear elements in its design. The transient response of a CCVT is, therefore, dependent on many factors. A subsidence transient occurs in the secondary following a fault on the primary system. A subsidence transient is an error voltage appearing at the secondary terminals due to a sudden drop in the primary voltage. In general, the CCVT response can show two different shapes. The first is a damped fast oscillation (200-2000Hz), predominant for primary fault near voltage crest. The second is a slow oscillation, predominant for a primary fault occurring near voltage zero [13,14].

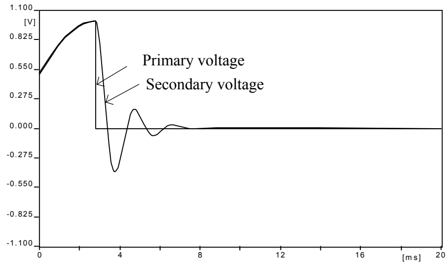

Fig. 13- Primary and secondary phase b voltage (p.u.)
(terminal "A" phase-to-ground fault)

Fig. 13, above, shows an example of a subsidence transient, obtained with the inclusion of the CCVT model in the simulated system of Fig. 2, for a terminal "A" phase-to-ground fault, at voltage crest of phase b. A damped fast oscillation secondary voltage (not following the primary voltage) can be seen, with a frequency around 500 Hz. It can also be seen in Fig. 13, that the steep characteristic of the primary voltage does not appear in the secondary voltage.

VII. SECONDARY VOLTAGE SPECTRUM

The results presented in this section are relative to secondary voltage measurements of phase b, in terminal "A". Fig. 14, 16 and 18 typify the results for phase-to-ground faults applied at 20, 70 and 210km from "A", respectively. Fig. 15, 17 and 19 show the Fourier analysis for the above voltages (fundamental frequency is 60 Hz). It can be seen that the components of fault induced transients with frequencies above approximately 1000Hz are considerably cut by the "low-pass filter action" of the CCVT (compare with Fig. 4 to 9).

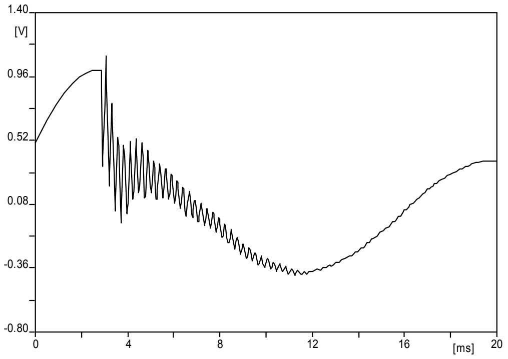

Fig. 14 Ph. b secondary voltage (p.u.), fault 20 km from "A"

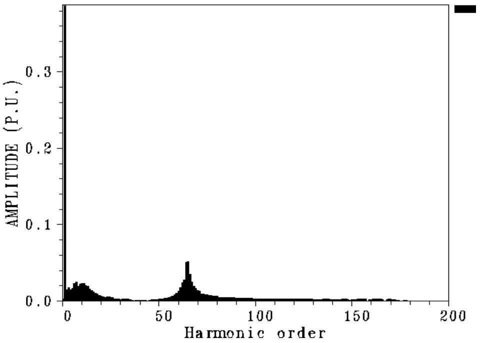

Fig. 15 Frequency spectrum of voltage in Fig. 14

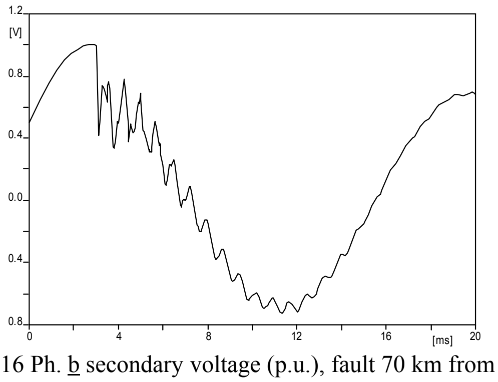

Fig. 16 Ph. b secondary voltage (p.u.), fault 70 km from "A"

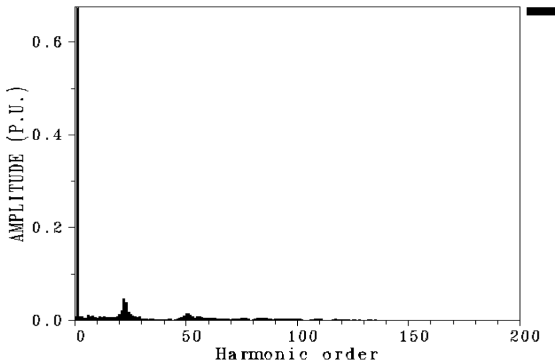

Fig. 17 Frequency spectrum of voltage in Fig. 16

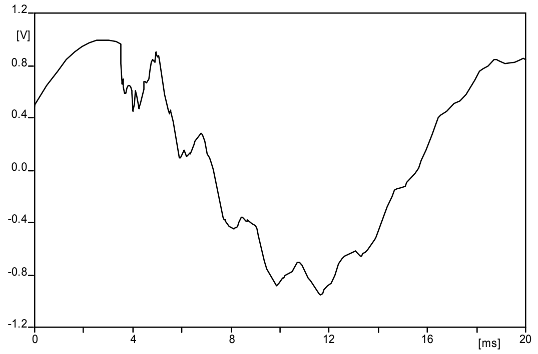

Fig. 18 Ph. b secondary voltage (p.u.), fault 210 km from “A”

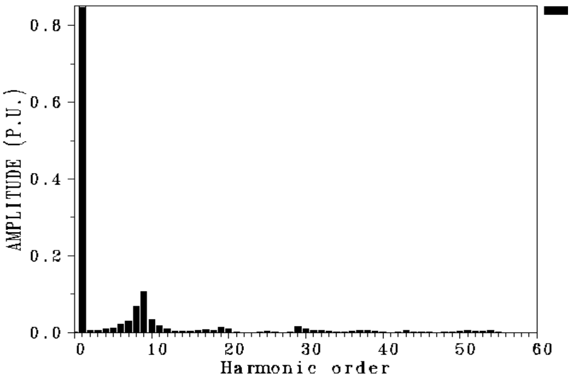

Fig. 19 Frequency spectrum of voltage in Fig. 18

Fig. 20 shows a comparison of primary and secondary voltages measurements in terminal “A” (Figs. 8 and 18 in another time scale), for a phase-to-ground fault 210km from terminal “A”. Again, it can be seen that the steep characteristic of primary voltage does not appear in the secondary voltage.

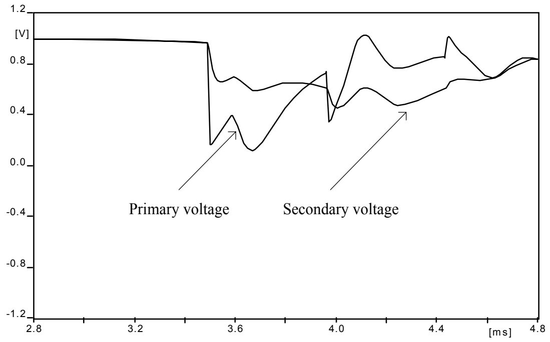

Fig. 20 Ph. b primary and secondary voltages (p.u.), phase-to-ground fault 210 km from “A”

VIII. HIGH FREQUENCY TAP

One can consider that a CCVT has two outputs. The first is the 60 Hz output, normally used to feed relays and meters in power substations. The previous sections have looked at the frequency response of this output and, by means of ATP simulations, how it works when submitted to fault induced transients. The second output is the high frequency output for the PLC, as shown in Figures 10 and 21. The PLC is a communication link between the two line terminals. Relatively high frequencies (typically 30-300 kHz), produced by electronic circuits, including oscillators and amplifiers, are transmitted utilizing the conductors of the line as a channel. In the same way, a fault induced transient contain high frequency components, that can be exploited in a traveling wave fault location system, in the spectrum of about 35 to 250 kHz [15]. The basic idea to be shown is: if the stack of capacitors can be used to couple the PLC electronic generated high-frequencies to the line, it can also be used to couple the high frequencies fault generated components to the control room, were the information to locate the fault will be captured.

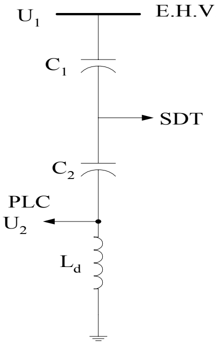

Fig. 21 – CCVT coupling circuit

The natural frequency response of the CCVT coupling circuit, obtained with the routine Frequency Scan of ATP, and plotted with MATLAB, considering typical data for C_1, C_2 and L_d , is shown in Fig. 22. The CCVT coupling circuit acts, naturally, as a two pole high-pass filter.

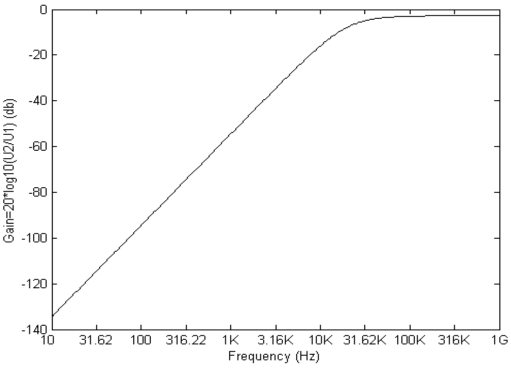

Fig. 22 – Freq. response of CCVT coupling circuit

An additional standard high-pass filter, that allows 30 kHz and above to go through it, is connected in series with the coupling circuit of CCVT, to ensure that only high frequency components of fault induced transients are sent to control room, where they can be processed [16].

IX. HIGH FREQUENCY TAP SIMULATION

In order to show that it is possible to capture the high frequency components of the fault induced transients, the high frequency tap was added to the system of Fig. 2, for the ATP simulations. A number of studies varying fault types, fault location, fault inception angles and fault resistance studies were run.

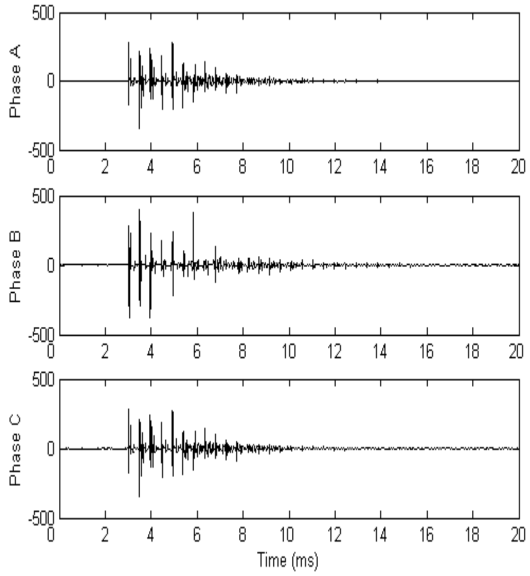

Fig. 23 – High-pass filter output, in terminal "A" (in volts)

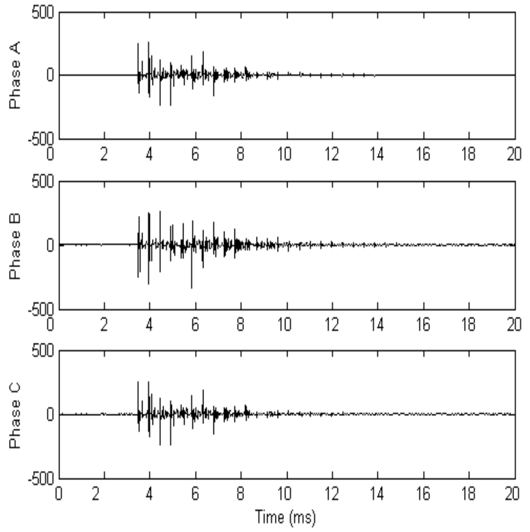

Fig. 24 – High-pass filter output, in terminal "B" (in volts)

Examples for a phase b to ground fault, located 70km from terminal "A" at voltage maximum, are given to illustrate the results obtained. Fig. 23 shows the output of the high-pass filter for phases a, b and c, in terminal "A", and Fig. 24 the same set of outputs for terminal "B". From these two outputs it is possible to capture the arrival time of the initial fault transient in both terminals. It is interesting to observe that, due to mutual coupling between the three line phases, it is possible to obtain this time information from any one of the three phases.

X. CONCLUSIONS

The results of the ATP simulations show that the steep characteristics of the traveling waves contained in the fault induced transients are not transferred to the CCVT secondary voltages.

The ATP results show that the CCVT high frequency tap, normally used for PLC application, does transfer the steep characteristics of the traveling waves, induced by fault transients, to its neutral side. In this way, it can be used as a mean to provide the information necessary for a traveling wave fault locator scheme.

Due to the mutual coupling of the line phases, it is possible to capture the traveling wave steep characteristics, using the high frequency tap, from any one of the line phases. So it is only necessary to install a fault locator in one phase, in each terminal of the line.

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