A COST EFFECTIVE SOLUTION FOR HIGH SPEED RECORDING IN EHV SYSTEMS

F Ghassemi*, J Merron*, Tom Cumming**, Finlay MacLeod***
* Qualitrol Hathaway Instruments, UK
** Scottish Power Systems, UK
*** PCS Ltd

1- INTRODUCTION

Instrument transformers are designed to give an accurate picture of EHV signals at the system frequency only. It is well known that capacitor voltage transformers (CVT) have inferior transient and frequency responses compared to other voltage transformers. The detrimental influence of CVTs on high speed relaying is well established and has been reported.

In recent years, there has been a tendency to offer higher sampling rate in monitoring instruments to try to capture fast changing events and in particular, voltage notches associated with solid-state devices, such as HVDC and FACTS. Sampling rates in the range of 12 and even 25 kHz are now on offer by fault recorder manufacturers. However, CVT response limits the advantages gained by higher sampling rates, as CVTs cannot transfer high frequency components accurately. A CVT model will be considered in the paper, which confirms that fast transients are not accurately reproduced by CVTs.

Reference [1] proposed a new method for CVTs that was originally proposed and is being used for power quality measurements, which has been further developed for fast transients, fault recordings and accurate phasor measurement applications.

The new technique is based on measuring currents in CVTs and involves minimal cost and time in retrofitting to installed CVTs or in modifications during the manufacture of new units. No change in the CVT design is required and the new accessory does not affect the normal operation of CVTs. This offers a cost effective alternative to using much more costly, dedicated voltage dividers or wound VT instrument transformers, which are often used for fast transient monitoring. The new technique offers an alternative signal to the CVT output, which is a true picture of the CVT terminal voltage. Simulation results and field measurements will be presented in the paper.

2- OPTIONS TO CONSIDER

If a utility is to carry out wide-bandwidth measurements such as transient and harmonic monitoring in extra high voltage (EHV) systems where the instrument transformers present, are only CVTs, then special high voltage divider is an or perhaps the only option to consider. Usually, CVT manufacturers offer voltage dividers in the form of mobile and fixed devices. Fig 1 shows a mobile, single phase, 500 kV voltage divider. This may be used in transient, such as line switching measurements as well as harmonic monitorings. Fig 2 illustrates a fixed divider installation where the dividers have been installed in parallel with the main CVTs. This is because dividers usually have very low output power and cannot be used to supply all metering and protection equipments. Furthermore, the transfer ratio and hence the output voltage depends on the burden size, hence if the burden changes the transfer ratio would change.

Fig 1- 500 kV Mobile Resistive Voltage Divider

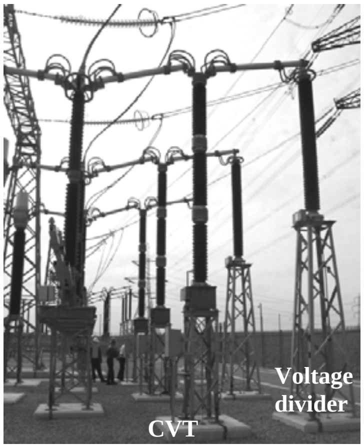

Fig 2- 400 kV Fixed Voltage Dividers

3- SENSORS TECHNIQUE FOR CVTS

The technique follows the Kirchhoff's circuit rule and involves no assumptions [1]. Consider Fig 3 that shows a typical CVT structure. Depending on the manufacturer and design, the voltage divider formed by HV and LV capacitors, C_1 and C_2 respectively, reduces the nominal system voltage to typical values between 5 to 12 kV. The internal circuit consists of the tuning reactor, step down transformer, magnitude and phase adjustment gear and Ferroresonance suppression unit.

Sensors are installed at the CVT earth points and measure currents in the CVT. The sensor outputs are then fed to the signal-conditioning module that converts the measured currents into the absolute terminal voltage. Note that the sensors are installed at earth potential and hence high insulation is not required. As a result, the sensors are small devices.

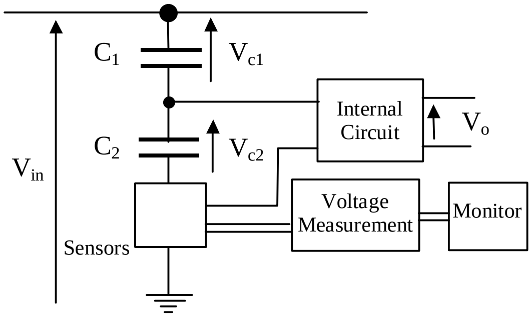

Fig 3. Circuit Diagram for a Typical CVT with New Voltage Measurement Capability

4- VERIFYING THE TECHNIQUE

In order to verify the technique, a 138 kV CVTs was simulated using the model and parameters given in Reference [2], which have been determined from the CVT made by a leading CVT manufacturer.

EMTP (ATP) was used to simulate the CVT model. The input and output voltages and also currents in the earth path were selected as EMTP output quantities, which are in the form of sampled data or time domain. Matlab package was used to simulate the voltage calculation algorithm devised in the signal-conditioning module to calculate the CVT terminal voltage.

Fig 4 shows the input voltage, which is the standard 1.2/50 μs impulses with a magnitude of 100 kV, produced by the EMTP.

Fig 5.a illustrates the output voltage of the CVT when the standard impulse voltage of Fig 4 was applied. The CVT appears to produce the front edge of the impulse accurately. However, a low frequency oscillation follows the impulse, which is mainly the result of interaction between the CVT's equivalent capacitance and the magnetising inductance of the intermediate transformer.

Fig 5.b illustrates the input voltage and calculated input voltage by the sensor technique on an expanded time axis. It can be seen that the new technique accurately reproduces the impulse.

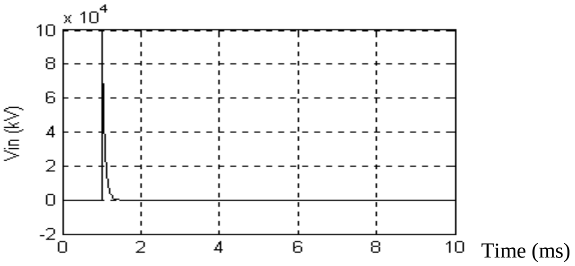

Fig 4- Input Voltage as the 1.2/50 μs Impulse
Time (ms)

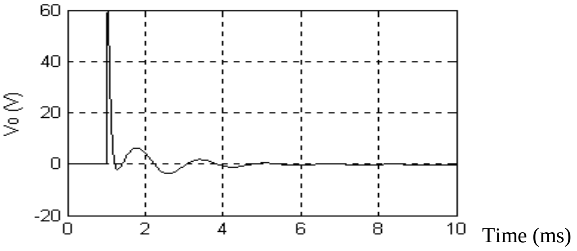

Fig 5.a- Output Voltage for the 1.2/50 μs Impulse Shown in Fig 2

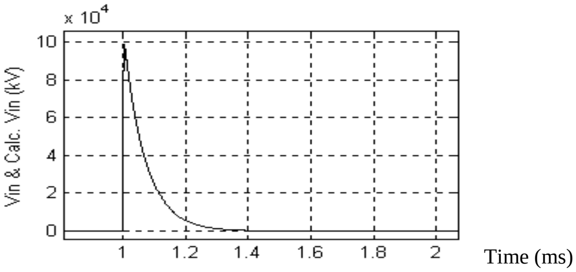

Fig 5.b- Input Voltage and Calculated Voltage by Sensor Technique for the 1.2/50 μs Impulse input

A series of simulation tests were carried out to examine the validity of the technique for sudden voltage changes in a fault condition. The source is a 50 Hz voltage source with finite source impedance equivalent to 1 GVA short circuit level (SCL). Source impedance angle is 84°. A 200 MVA resistive load was considered. The CVT burden is 100 VA with a power factor of 0.85.

Typical fault recorders with dynamic system monitoring perform the Fourier transform on a cycle-by-cycle basis to extract the fundamental frequency component. Matlab was used on the EMTP sample data to compare the magnitude of the fundamental of the input voltage with the sensor derived input voltage and the standard CVT output voltage. The results are shown in Fig 6.a. The sampling rate of the EMTP data is 6.4 kHz. Fig 6.b illustrates the error between the input voltage, the calculated sensor voltage and the CVT output voltage when the input voltage has been taken as the reference. It can be seen that the error of the sensor derived input voltage is nearly zero. The error of the CVT output voltage is high during the initial cycle after fault inception. The error in phase also follows the same pattern.

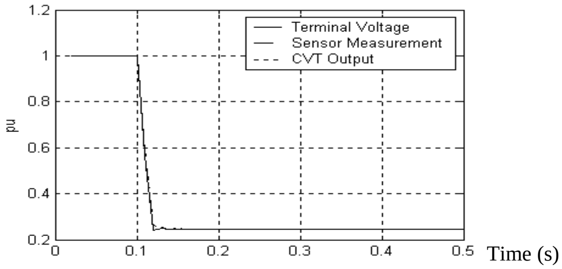

Fig 6.a- Magnitude of Input and Output Voltages and Calculated Voltage by Sensor Technique for a Fault

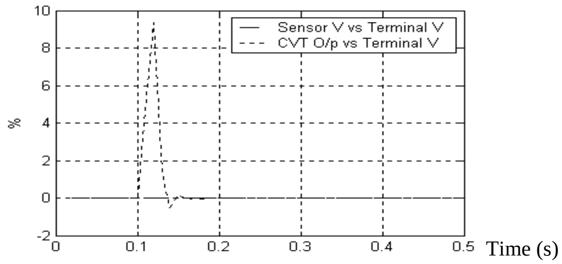

Fig 6.b- Magnitude Error Between Input and Output Voltages and Calculated Voltage by Sensor Technique for a Fault

Response of the CVT and the sensor technique for capacitor switching are examined by simulating a system, which consists of a source with a SCL of 5 GVA, load current of 300 A and a 100 MVA power factor correction capacitor. The CVT burden is 70 Ω resistive. Fig 7.a shows both the input voltage and the sensor measurement when the capacitor is switched. Note that they are so similar that they appear as one trace. Fig 7.b illustrates the CVT output voltage for the same condition. Note that the CVT cannot reproduce the actual notch depth when the capacitor is switched. Furthermore, a damped high frequency oscillation is superimposed on the CVT output voltage. This confirms that the CVTs and not the capacitor switching may cause some of the oscillations observed on records from practical systems.

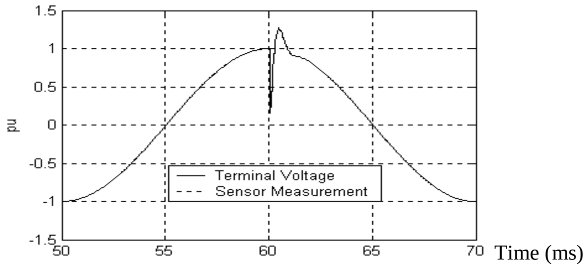

Fig 7.a- Terminal and Sensor Voltages for Capacitor Switching

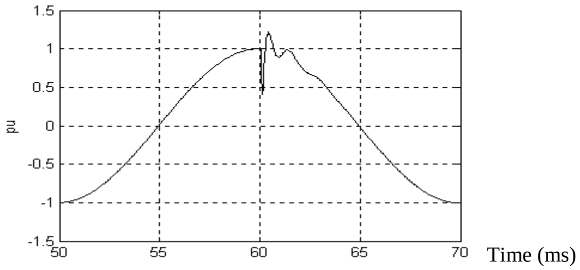

Fig 7.b- Output Voltage for Capacitor Switching

5- DOES IT WORK IN PRACTICE?

Reference [1] gives a number of laboratory and field measurement results that confirm the validity of the technique.

In Scotland two three-phase units were installed in two substations. A disturbance recorder with power quality measurement capability monitors the sensors. A separate recorder was connected to the same CVT normal output terminals. The installation is shown in Fig 8. No faults or large disturbances occurred close to the CVT during the measurement period although the system recorded some events and through faults when the busbar voltage slowly changed by about 20%. Figs 9.a to 9.c illustrate the digital fault records (DFR) of both voltages recorded from the CVT and Sensor technique for three phases. As can be seen the difference between the two measurements is minimal. This event appears to be a three-phase phenomenon that caused a slow change in voltage, perhaps a large power swing. Fig 10 shows the rms calculation of the voltages shown in Fig 9.a. This is known as continuous slow scan or CSS record. The signal rms value is calculated on the cycle-by-cycle basis and the window of measurement is moved by half a cycle. The maximum error between the two CSS records for each phase is about 0.5%, which is well within the accuracy of the monitors.

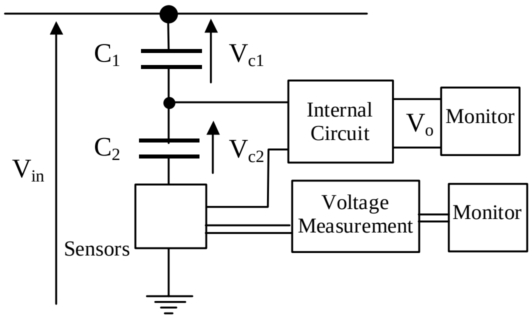

Fig 8- Power Quality Measurements Using CVT

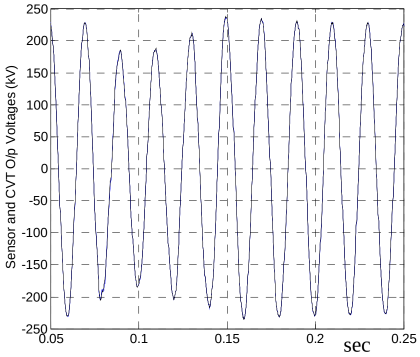

Fig 9.a- Phase “a” Sensor and CVT O/P for a Disturbance

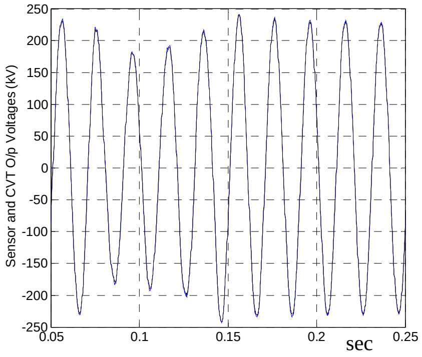

Fig 9.b- Phase “b” Sensor and CVT O/P for a Disturbance

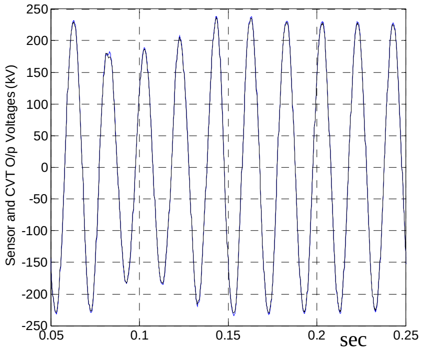

Fig 9.c- Phase “c” Sensor and CVT O/P for a Disturbance

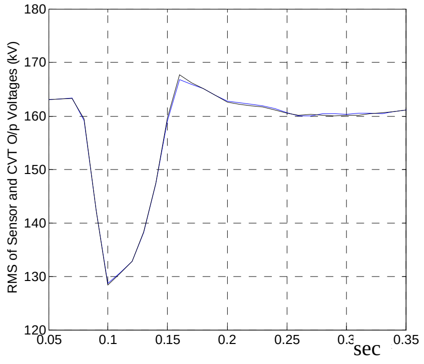

Fig 10- Sensor and CVT RMS calculation for Fig 9.a

A series of tests were organised in Thailand to investigate switching over-voltages in a 500 kV transmission system, which consisted of a triple circuit, 300 km long lines. The objective was to investigate the voltage at the open end when one of the lines is switched from the other end. The other two lines remained energised and carried load during the switching. Three 500 kV, mobile, single-phase resistive dividers were used as the interface between the power system and the instrumentation. Fig 1 illustrates a single-phase divider used in the tests. Sensors were also installed in all three CVTs, which were manufactured by the same manufacturer as the CVT modelled in this paper. The sensors did not interfere with the CVTs output voltages and the CVT output terminals remained connected to the protection systems and meters in the normal way. No extra substation space was required to install the sensors. A typical installation is shown in Fig 11.a and 11.b. The Sensor signal-conditioning module is mounted on the CVT stand and the sensors are placed in the CVT terminal box. Two different instruments with sampling rate of 12.8 kHz and 6.4 kHz were used respectively to measure the voltage from the resistive divider and from the sensors. Hence, with the claimed bandwidth of the divider and higher sampling rate one expected to capture high frequency components on the system voltage more accurately than the sensors.

Fig 12 illustrates phase b voltages measured through the resistive dividers. Fig 13 shows the same voltage measured by the sensors.

It can be seen that the error between the measurements are extremely small. A close inspection of the results confirms that the only difference is in the higher frequency region of the spectrum where the divider was not able to reproduce the components accurately.

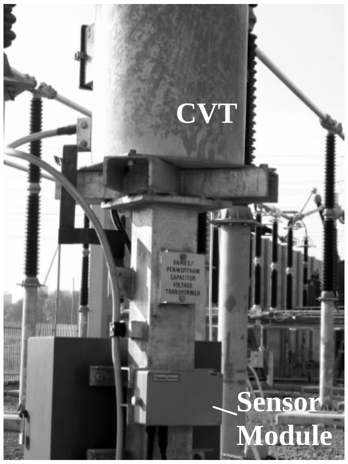

Fig 11.a- Sensor Module Mounted on a CVT Stand

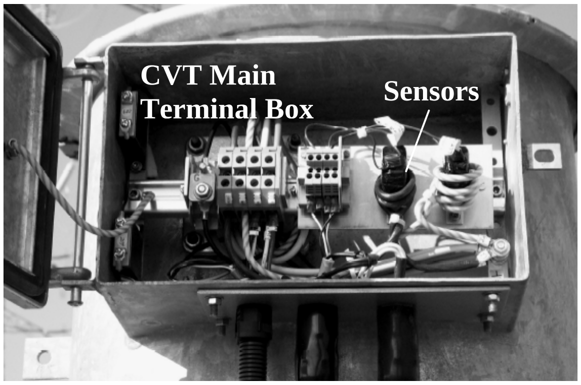

Fig 11.b- Sensors in A CVT Terminal Box

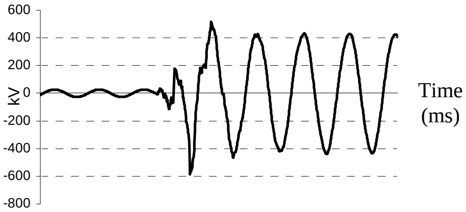

Fig 12- Phase b Voltage Measured by the Voltage Divider

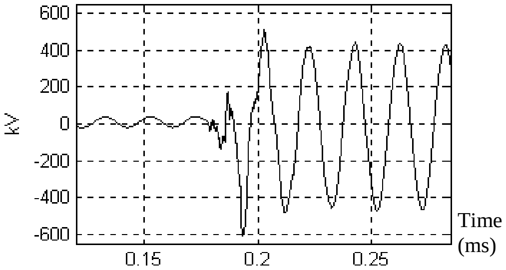

Fig 13- Phase b Voltage Measured by the Sensor Technique

6- COMPARISON OF FAULT RECORDS

As was mentioned before, during the measurement period no fault occurred on the line or close to the CVT. However, some faults on the system caused the monitors to trigger. A single phase to ground fault, which appeared to be close to the busbar occurred on January 11, 2005 at 13:57. This fault caused a voltage dip and at the same time a line current reduction, indicating that the fault was upstream with respect to the measurement point.

Fig 14 shows the measured voltage by the sensor and CVT. Fig 15 illustrates the CSS records from the two signal sources. There are three major differences between the two measurements. First, the difference between the two CSS records is much larger than previously shown for a slow changing event, see Fig 10. A difference of 12% is observed between the two measurements during the fault period. Second, the CVT output voltage shows high frequency oscillations with high magnitudes. This is in agreement with the harmonic measurement results presented in Reference [1], which indicated the presence of a resonance in the frequency response of the same CVT. Inspecting the frequency content of the fault record reveals that there might be a resonance in around 1.1 to 1.4 kHz.

Third, difference between the phase angle measurements is much larger. A difference of 6 degrees during the fault period is observed.

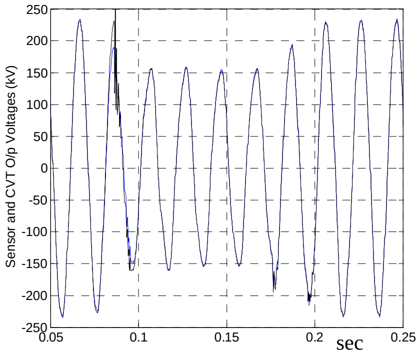

Fig 14- Sensor & CVT Voltage for a Fault Upstream

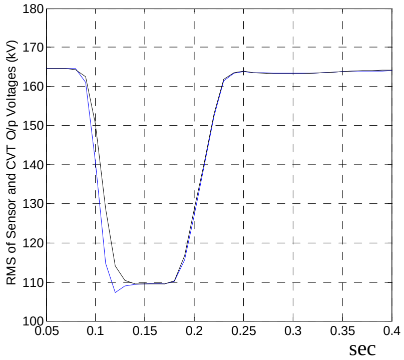

Fig 15- CSS Records of Sensor & CVT Voltage for a Fault Upstream

A fast transient disturbance was recorded by the monitor connected to the Sensors on 14th December 2004 at 15:48. The monitor connected to the CVT output did not trigger for this event and hence no record is available from the CVT output. Figs 16.a and 16.b illustrate Phase “a” and “c” voltage measurement respectively for the disturbance. Phase “b” voltage shows a slight decrease and hence is not shown here. It can be seen that the disturbance lasts for a short time. Phase “a” shows an increase of about 11% and Phase “c” dropped by about 18% for a very short time. The trigger threshold in both monitors were set at 10% over and under voltages. Fig 17 illustrates the CSS record for Phase “c”. Fig 18 shows the 10 second CSS record from the monitor connected to the CVT output, which confirms that the event has affected the measurement. However, the depth of the voltage change has not been accurately transferred by the CVT to cause the monitor to trigger. This may be attributed to the slow response time of the CVT.

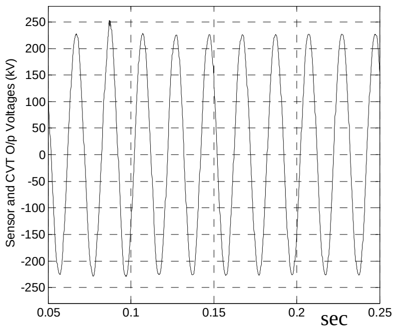

Fig 16.a- Sensor Measurement for Fast Transients, Phase “a”

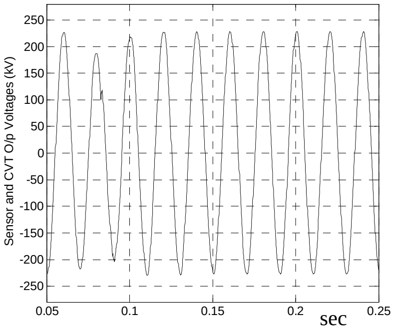

Fig 16.c- Sensor Measurement for Fast Transients, Phase “c”

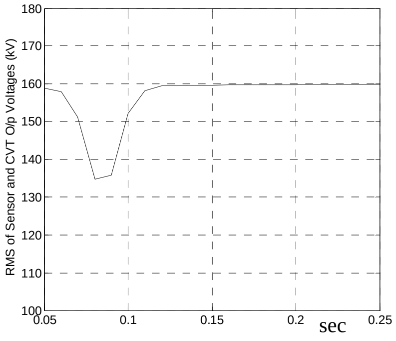

Fig 17- CSS Record for Sensor Measurement for Fast Transients, Phase “c”

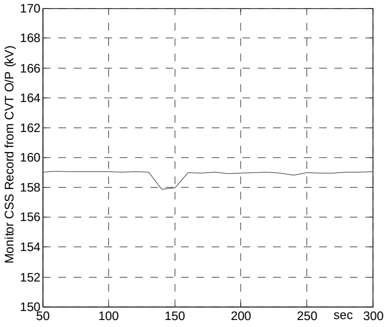

Fig 18- Ten Sec CSS Record from the Monitor Connected to the CVT O/P

7- CONCLUSIONS

The new technique for high frequency, high-speed transient measurements using CVTs was examined by simulation and field tests. It was shown that the new technique, which is based on the measurement of currents in CVTs can be used to monitor fast transients without any need for special high voltage instrument transformers or wide bandwidth voltage dividers.

Field measurements showed very good correlation between the CVT standard output and the sensor technique in steady state and for slow changing events and also between the measurements by the new technique and those obtained through resistive voltage divider. A difference was observed in the higher frequency range where the divider was unable to reproduce the primary voltage signal accurately.

The results obtained from a CVT simulation was confirmed through field measurements. Two main effects may be expected from a CVT, slow response time to a fast changing phenomenon and producing oscillations on the CVT output when a relatively large change in voltage occurs close to the CVT. Both effects have been well known. Comparing the results obtained from the CVT output and the Sensors revealed that the CVT that was used in the measurement produced the same characteristic.

A relatively close single-phase-ground fault caused some high frequency components to appear in the CVT output that were not measured by the monitor connected to the Sensors. Inspection of the results showed that the CVT frequency response might have a resonance at around 1.1 to 1.4 kHz.

The monitor connected to the Sensors recorded a fast and short disturbance. This event did not trigger the monitor connected to the CVT output. The depth of the disturbance was less than half a cycle. This may be attributed to the fact that the CVT is not capable of responding to fast changes accurately and quickly.

The Sensor technique offers a cost effective solution to presently available alternatives in the market for wide bandwidth measurements in EHV systems.

8- ACKNOWLEDGMENT

The authors wish to express their gratitude to Scottish Power Plc (SP) for their collaboration and permission of using test results.

9- REFERENCES

1. Ghassemi F, et al. “Harmonic Voltage Measurements Using CVTs”, IEEE Trans. Power Delivery, Vol. 20, No. 1, January 2005, pp 443-449.
2. Iravani M R, et al, “Digital time-domain investigation of transient behaviour of coupling capacitor voltage transformer,” IEEE Trans. Power Delivery, Vol. 13, No. 2, 1998, pp. 622-629.