HARMONIC RESPONSE TESTS ON VOLTAGE TRANSDUCERS
FOR THE NEW ZEALAND POWER SYSTEM

D.A. Bradley, Non-Member
University of Lancaster
Lancaster, England.

P.S. Bodger, Non-Member
University of Canterbury,
Christchurch, New Zealand

P.R. Hyland, Non-Member
New Zealand Electricity

Abstract - This paper presents the results of harmonic response tests carried out on capacitive voltage transformers, as used on the New Zealand 220 kV a.c. network. It is shown that the harmonic response measured using low voltage test equipment is considerably different from that obtained at high voltage. The latter is highly non-linear and is affected by the specific magnetization characteristic of the CVT tested. It is concluded that for field measurement of harmonics at rated voltage, the transformer of a CVT unit should be disconnected and the CVT used as a purely capacitive or resistor-capacitor divider.

INTRODUCTION

The New Zealand legislation for the control of power system harmonic content [1] sets out both the permitted levels of harmonic currents and voltages and the way in which these levels are to be measured. In particular, the overall accuracy of the measurement system, including the transducer, to be used for obtaining system harmonic voltages is specified as 0.1 percent of the nominal system phase to earth voltage. The effect of this requirement, expressed in terms of transducer ratio and ratio error, on the measurement system is shown in figure 1.

Whilst voltage transducers of defined accuracies at fundamental frequency are available for power system use; where measurements involving harmonics are concerned, the performance of these transducers requires further consideration.

Douglass [2] has tested magnetic units to 7.2 kV primary voltage and has shown that, depending on burden, a linear response can be obtained to 2 or 3 kHz. Cornfield [3] has also reported a linear response to 1 kHz for 11 kV units. For magnetic transformers operating at higher voltages CIGRE [4], Casu and Simoncini [5] and Malewski and Douville [6] all report responses which exhibit significant variations in transformation ratio with frequency. Oliver et al [7] have also considered the cascade connection of magnetic units with similar observed effects.

At higher voltage levels magnetic voltage transformers are often replaced by capacitive voltage transformers (CVT's) for measurement purposes. CIGRE and Casu and Simoncini have reported on the behaviour of these units in the presence of harmonics where significant variations from the nominal, fundamental frequency, transformation ratio, are again shown.

These reported results serve to indicate the nature of the problems likely to be encountered when using magnetic or capacitive voltage transformers for harmonic measurements. The results are, however, device specific and of little assistance in predicting the performance of other units. Also, with the exception

of Casu and Simoncini, the procedures and the nature of the harmonic source used to test the higher voltage transformers is largely unspecified.

New Zealand Electricity therefore decided to evaluate the performance of available transformers both to establish references for use with harmonic measuring systems and to examine test procedures. In particular, the possibility of calibrating transformers for harmonic measurement using low voltage techniques was to be investigated. As it was felt that the level of core saturation would influence the harmonic response, the effect of variation in the level of the fundamental voltage was also to be examined.

The transformer chosen for these tests was the Artech DFC-245 CVT, a number of which were currently installed or being installed at sites on the South Island system. This unit was chosen as its design allowed the magnetic unit to be disconnected, enabling the capacitive divider stack to be used as the basis for a capacitive or series RC divider.

LOW VOLTAGE MEASUREMENTS

Low voltage measurements require simple equipment and can be performed in almost any location. The only limitation is the level of electrical noise present which can interfere with the readings being made. It was not anticipated that the low voltage tests would mirror the full voltage behaviour of magnetic or capacitive voltage transformers. Rather it was intended to establish if any relationship did exist between measurements made at low and full voltage which would enable a simple calibration procedure to be evolved.

In practice it was found impossible to perform any low voltage tests in the transformers' normal operating environment within the high voltage switchyard, as the levels of electrical noise picked up by the units themselves prevented any measurements from being made. When the measurements were later repeated in an electrically quiet location, the results of tables 1 and 2 and figure 2 were obtained. These show good agreement with the theoretical response for the capacitive and series RC dividers, the errors being well within those set by the instrumentation used.

FIELD HIGH VOLTAGE MEASUREMENTS

Following the example of Casu and Simoncini it was decided to use the 220 kV system itself as the harmonic source for the tests. The site chosen was the southern end of the inter-island d.c. link at Benmore Power Station (figure 3). This site was selected as earlier measurements had revealed a high harmonic content.

For the first series of high voltage tests, an ASEA resistive divider (reference), one CVT in its normal operating configuration but with no burden connected and a second CVT with its primary magnetic circuit disconnected and a capacitor, across which the output would be taken, inserted at the base of the divider stack were connected to the 220 kV busbar. Harmonic levels indicated by each unit were to be measured using Plessy Selective Audio Frequency Power Analysers (SAFPA's) [8], one to each unit. As these instruments are only capable of monitoring a single frequency, a Wandel and Goltermann NOWA-1 Fourier

84 SM 687-0 A paper recommended and approved by the IEEE Power Systems Instrumentation & Measurements Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1984 Summer Meeting, Seattle, Washington, July 15 - 20, 1984. Manuscript submitted January 30, 1984; made available for printing June 6, 1984.

(a) Permitted transducer and instrument errors by harmonic

(b) Effect of variation in transducer ratio on permitted transducer and instrument errors for 11th harmonic

Figure 1. Effect of transducer ratio error on harmonic measurement

Table 1. Capacitive divider ratio

Theoretical ratio	991.1:1
Measured ratio at 50 Hz	1008.7:1
500 Hz	1008.6:1
1000 Hz	1007.3:1
1500 Hz	1006.4:1
2000 Hz	1004.6:1
2500 Hz	1001.3:1
Maximum error (Measured:Theoretical)	+1.91% @ 200 Hz
Minimum error (Measured:Theoretical)	+1.03% @ 2500 Hz

Table 2. Series RC divider ratio

Ratio at	Measured	Theoretical
50 Hz	1599:1	1570:1
500 Hz	160:1	159:1
1000 Hz	80.2:1	78.5:1
1200 Hz	66.7:1	65.4:1
1600 Hz	50:1	49.1:1
2000 Hz	39.9:1	39.3:1
2500 Hz	31.9:1	31.4:1
Maximum error (Measured:Theoretical)	+2.22% @ 600 Hz	
Minimum error (Measured:Theoretical)	+1.49% @ 2300 Hz

Figure 2. Single frequency response of CVT derived from low voltage (300 V) measurements

Transform instrument was also available for full spectrum data.

On energisation of the 220 kV busbar the harmonic voltage spectrum of figure 4 was measured using the NOWA-1 at the output of the resistive divider. Whilst this represents a very satisfactory condition for the operating engineers, with no harmonic having an amplitude in excess of 0.75 percent of the fundamental amplitude, it was of no use for the primary purpose of the tests, that of establishing transducer performance.

A change from 12-pulse to 6-pulse operation together with some load shedding on the d.c. link increased the harmonic levels to those of figure 5. However, under these conditions the SAFPA's proved incapable of providing adequate resolution since their range setting is determined by total harmonic content and not the amplitude of the frequency being monitored. This meant that the indicated readings for individual harmonics lay in the bottom third or less of the instrument range and therefore were subject to unacceptably large errors.

Additionally, the harmonic levels obtained with 6-pulse operation fluctuated rapidly as the d.c. link loading varied and the SAFPA's proved unable to track the lower amplitude harmonics. The minute to minute variation of harmonic amplitudes was observed using the NOWA-1. The extent and rate of variation did, however, combine to prevent any comparative measurement being made between the units under test as only a single NOWA-1 was available at the test site.

UNIVERSITY OF CANTERBURY HIGH VOLTAGE LABORATORY TESTS

Following the failure of the field tests it was decided to conduct a further series of tests in the more controlled environment of the University of Canterbury High Voltage Laboratory. This laboratory is equipped for conventional high voltage testing, and in common with other such laboratories, lacks a controllable source of high voltage harmonics capable of being superimposed on a full voltage fundamental. It does, however, have a Heafely Chopping Gap/Parallel RC divider which would function as an impulse divider and

Figure 3. New Zealand inter-island d.c. link

Figure 4. Benmore power station, initial harmonic levels

Figure 5. Benmore power station, final harmonic levels

could be used as the reference divider.

Harmonic Voltage Source

For the purpose of establishing the transducer response, the chief requirement was for a source producing a sufficient range of stable harmonics for a comparison to be made with the reference. The accurate control of individual harmonics which would be required for full instrument and measurement system calibration was not considered necessary at this stage.

After consideration of various alternatives, the back to back thyristor pair of figure 6 was introduced between the regulator and the step-up transformer. By using individual firing angle control, asymmetry can be introduced into the low voltage side of the step-up transformer producing even harmonics in the high voltage system.

Though this arrangement did not produce a particularly large range of high voltage harmonics, it did provide a reasonably stable source and was used for all high voltage measurements.

Figure 6. Configuration for the production of harmonics at the University of Canterbury High Voltage Laboratory

High Voltage Tests

In this series of tests each transducer was connected in turn to the high voltage system in parallel with the reference transducer. A NOWA-1 was then used to record the harmonic spectra obtained on each transducer. By switching the instrument between the transducers, a series of readings for output harmonic spectra was obtained and the comparison then made in terms of the average values obtained for each transducer at the individual harmonics.

The major difficulty with this procedure, which was necessitated by the availability of only one NOWA-1 instrument, lies in the stability of the harmonics applied to the transducers. Low amplitude harmonics, of less than 1 percent of the fundamental amplitude, were subject to variations in level of up to 30 percent between readings. Whilst averaging over a number of readings minimised this effect, the results obtained reflect this particular problem.

Capacitive divider:

The output wave forms of the reference transducer and the capacitive divider are shown in figure 7 together with their associated spectra. From these the equivalence of the responses can be seen, as is to be expected, as both have constant nominal ratios with frequency. Table 3 compares the performance of the capacitive divider with that of the reference divider by calculating the effective system voltage at each frequency using the reference divider ratio and the results of table 1. The calculated system voltages for the reference and the capacitive divider based on their output voltages V_{ref} and V_c are given by HV_{ref}^{cal} and HV_c^{cal} respectively. The table shows that generally good agreement was obtained with increased error for lower amplitude harmonics.

Table 3. Comparison of harmonic voltages measured using the reference divider and capacitive divider

Harmonic	V _{ref}	HV _{ref} ^{cal}	V _c	HV _c ^{cal}	%Error
1	291.1	125330	125.2	126250	+0.73
2	38.1	16410	16.3	16450	+0.27
3	56.5	24630	24.2	24430	+0.31
4	20.9	9000	8.97	9060	+0.67
5	19	8185	8.15	8215	+0.35
6	7.24	3120	3.12	3150	+0.94
7	6.14	2650	2.64	2665	+0.61
8	0.867	374	0.367	370.3	-0.96
9	0.853	367.7	0.373	376.3	+2.35
10	1.4	603.4	0.597	602.1	-0.21
11	0.7	301.7	0.287	289.4	-4.08
12	1.17	504.3	0.483	487.2	-3.39
13	0.493	212.4	0.223	224.9	+5.88

Series RC divider:

The output waveforms of the reference transducer and the series RC divider are shown in figure 8 together with their associated spectra in which the influence of the RC divider in emphasising the higher order harmonics is readily apparent. Table 4 gives the comparison of the performance obtained using computed ratios in a manner similar to that of table 3. Again a generally good agreement is obtained with increased error at lower harmonic amplitudes.

Capacitive voltage transformer

The harmonic spectrum of the CVT at full voltage is shown in figure 9, together with the corresponding spectrum for the reference transducer. The influence of the CVT is readily apparent. This result may be expressed in terms of ratio variation with harmonic frequency and plotted as figure 10. As can be seen, there is

Table 4. Comparison of harmonic voltages measured using the reference divider and the series RC divider

Harmonic	V _{ref}	HV _{ref} ^{cal}	V _{RC}	HV _{RC} ^{cal}	%Error
1	296.7	127770	80.6	128900	+0.88
2	48.7	20980	26.33	21100	+0.57
3	52.33	22560	42.5	22630	+0.32
4	26.9	11600	29.13	11655	+0.47
5	17	7320	23	7364	+0.6
6	10	4312	16.37	4370	+1.34
7	5.14	2216	9.83	2252	+1.62
8	2.1	906	4.54	908	+0.02
9	0.383	165.1	0.843	149.9	-9.21
10	0.677	291.8	1.97	315.3	+8.06
11	1.04	448.2	3.11	452.9	+1.05
12	0.95	409.5	3.21	428.8	+4.71
13	0.75	324.5	2.53	311.8	-3.91

considerable variation in effective ratio with harmonic frequency. In addition, the response is very different from that obtained at low voltage and single frequency when the magnetic core was subject to a very low level of flux.

This difference between the full and low voltage responses was not unexpected as it was felt that the level of flux in the core of the magnetic unit must play a significant role in determining the overall behaviour. No prior attempt had been made to model the behaviour of the CVT, as simple linear models such as that of figure 11 were considered inadequate and insufficient data was available to achieve a more accurate model.

To establish the influence of the magnetic circuit on the CVT performance, and to collect information for proper modelling of the CVT, a further series of frequency response measurements were performed with reducing fundamental voltage levels. The results of these tests are shown in figure 12. In particular, a transition between two response forms was observed with the higher voltage response being characterised by a peak at 450Hz. This peak was then absent from the low voltage responses which in turn approximated to the form of the low voltage, single frequency response curve. It was found that it was possible to establish a condition in which the inherent variation in fundamental voltage level of a few hundred volts resulted in the transition between the two modes. This is shown in figure 13. The particular voltage level at which this occurred varying from unit to unit.

From these results it was felt that the transition voltage and the change between modes must be associated with a change in the incremental value of magnetizing inductance as the core flux was varied. Attempts to explain the response using the simple model of figure 14 for core behaviour proved unsuccessful. In particular no satisfactory mechanism for the observed peak at 450Hz, which required an increase in the value of incremental inductance could be obtained.

Once the full series of high voltage tests was completed the magnetizing characteristic of the core was obtained by the excitation of one of the low voltage windings with the primary and other low voltage windings open circuited. The results of these measurements are given in figure 15. These curves exhibit a three part characteristic as opposed to the conventional, two part curve of figure 14.

Comparison of this curve with the CVT response curves of figure 12 (CVT 1) indicated that the first transition point, associated with an increase in the incremental inductance level, corresponded to the voltage level at which the transition between modes was occurring. This form of magnetization curve is observed in data from various manufacturers of magnetic steels.

Figure 7. Output waveforms and harmonic spectra for reference and capacitive divider

(a) Output of reference

(b) Output of series RC divider

Figure 8. Output waveforms and harmonic spectra for the reference and series RC dividers

Figure 9. Output harmonic spectra of reference and CVT with 127 kV primary voltage

These results have demonstrated the influence of the magnetizing characteristic of the transformer steel on CVT behaviour. Limitations imposed by available equipment have thus far prohibited the extension of the response curves to the full frequency range and to voltages significantly in excess of the normal operating voltage

Figure 10. Frequency response of CVT with 127kV primary voltage

Figure 11. Transformer equivalent circuit

(a) Fundamental voltage=98.1kV (b) Fundamental voltage=93.8kV (c) Fundamental voltage=61.7kV

Figure 12. Effect of variation of fundamental voltage magnitude on CVT frequency response characteristic. (CVT 1)

Figure 13. Variation of CVT frequency response characteristic (CVT No. 2).

Figure 14. Two part magnetization characteristic

Figure 15. Magnetization characteristic of core of CVT No 1 (corresponds to figure 12).

DISCUSSION

The tests described have demonstrated the problems of using CVT's for measurements in the presence of harmonics. It should, however, be noted that the ratio obtained for the fundamental frequency component remained constant throughout.

The possibility of using the particular CVT tested as the basis for both capacitive and series RC dividers whose response can be determined from simple measurements of component values, was demonstrated. As a number of the particular type of CVT are already installed or being installed on the New Zealand Electricity system, this could make available a number of units which could be used for harmonic measurements.

The tests also established the need for a high voltage test facility capable of testing and calibrating harmonic measuring systems and measuring system components. This need is particularly acute in New Zealand, given the particular nature of its regulations governing system harmonic content and the demonstrated impossibility of relying on the power system as a harmonic source for calibration purposes.

Based on the above, the following areas have been identified for further work:

(i) The development of operational procedures to enable CVTs to be used as either capacitive or series RC dividers for harmonic measurement. This includes the provision of appropriate, isolated data transmission links and associated protection. There is also the possibility of introducing amplifier based transducers such as those described by Lisser [9] and others for use on capacitive dividers or loss tangent taps.

(ii) The need to develop a high voltage harmonic injection system for use in conjunction with existing facilities. This system should provide either single or multiple harmonics up to 2500Hz superimposed upon a full voltage fundamental and will be used as a reference and calibration source for future measurement and testing.

(iii) The development of a suitable CVT model for analysis purposes. Though it is recognised that individual differences between CVTs mean that full voltage testing will be required to properly establish behaviour, this model is necessary to the proper understanding of such behaviour. In addition to the application of non-linear analysis techniques, a low voltage test transformer is being developed with which it is hoped to simulate the behaviour of the full scale CVT.

CONCLUSIONS

The tests conducted by New Zealand Electricity have confirmed the previously published results as well as demonstrating the problems associated with making measurements of this type.

Of particular importance is the influence of the fundamental voltage magnitude upon the frequency response obtained. The variations in this response that occurred for small changes in fundamental voltage amplitude near the nominal operating voltage, were such as to prevent the production and use of a calibration curve for a particular transformer.

Further, the need for the provision of a suitable harmonic source, capable of supplying a full range of harmonics at full system voltage, has been recognised.

ACKNOWLEDGEMENTS

The authors would like to thank New Zealand Electricity and the University of Canterbury for the provision of facilities during the course of the work described. They would also like to thank the General Manager of New Zealand Electricity for permission to publish this paper.

REFERENCES

- 1 Electricity Division of the Ministry of Energy, "New Zealand Limitation of Harmonic Levels Notice (1981)", First Issue, December 1981.
- 2 D.A. Douglass, "Potential transformer accuracy at 60Hz voltages above and below rating and at frequencies above 60Hz", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 3 pp 1370-1375, March 1981
- 3 G.C. Cornfield, "Record of Discussions", CIRED, Brighton, IEE Conf Pub 197, pT 2, pp 48, 1981
- 4 CIGRE Working Group 36-05 (Disturbing Loads) "Harmonics, characteristic parameters, methods of study, estimates of existing values in the network" Electra, No 77, pp 35-54, July 1981
- 5 A. Casu and V. Simoncini, "Harmonics due to rectifiers connected to the Sardinian 220kV AC network", IEE Conf Pub 110, pp 215-255 22-24 April 1974
- 6 R. Malewski and J. Douville, "Measuring properties of voltage and current transformers for the higher harmonic frequencies", Canadian Communication and Power Conference, Montreal, pp. 327-329, October 1976
- 7 G. Olivier, R.P. Bouchard, Y. Gervais and D. Mukhedkar, "Frequency response of HV test transformers and the associated measurement problems", IEEE Transactions on Power Apparatus and Systems, Vol PAS-99, No. 1, pp 141-146, January/February 1980
- 8 L.N.M. Edward, J. Arrillaga, N.W. Ross and J.F. Baird, "Harmonic measurement and the Selective AF Power Analyser", CIRED, Brighton, IEE Conf Pub 197, pp. 81-85, 1981
- 9 J. Lisser, "High accuracy with amplifier type voltage transformers", Electrical Review, Vol. 198 No. 21, pp. 31-33, 28 May/4 June 1974