INVESTIGATION GUIDE

NOISE

INTERFERENCE

NZCCPTS

Issue 1

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The New Zealand Committee for the Co-ordination of Power and Telecommunication Systems Inc. (NZCCPTS)

The New Zealand Committee for the Co-ordination of Power and Telecommunication Systems was established in 1985 following the increasing need to implement efficient cost-effective measures for the limitation of hazard and interference to Power and Telecommunications Systems and Personnel.

Such measures not only require the determination of optimum engineering solutions consistent with minimum national cost, but also necessitate clear guide-lines covering the equitable allocation of responsibilities during all work phases from planning through to in-service operation.

The objective of the New Zealand Committee for the Co-ordination of Power and Telecommunication Systems is to meet these needs and, by means of publications and seminars, promote a greater awareness and understanding of the action that must be taken to ensure that Power and Telecommunication Systems coexist satisfactorily.

Membership of the Committee and its Working Parties currently comprises representatives for each of the following organizations:

- Electricity Engineers' Association of New Zealand (Inc.)
- Energy Safety, WorkSafe NZ, Ministry of Business Innovation and Employment (MBIE)
- Chorus New Zealand Ltd
- Transpower New Zealand Ltd
- KiwiRail (KiwiRail Holdings Ltd)

For further information concerning this Committee and its published guides, contact the Secretary of NZCCPTS via email to secretary@nzccpts.co.nz, or via his contact details on the ‘Contact Us’ page of the NZCCPTS website (www.nzccpts.co.nz).

GUIDE FOR INVESTIGATING AND MITIGATING POWER SYSTEM – TELECOMMUNICATION SYSTEM NOISE INTERFERENCE

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Foreword

This guide provides information on the causes and characteristics of power system disturbing current phenomena, and presents guidelines for systematically investigating and mitigating cases of reported telecommunication systems interference.

Acknowledgements

NZCCPTS is indebted to the Electricity Engineers' Association of New Zealand, Telecom New Zealand Limited, and Transpower New Zealand Limited, for their contributions in the formation of this guide.

Comments for revision of this guide are welcomed. Any comments or information that may be useful for inclusion in this guide should be forwarded to the Secretary of NZCCPTS via email to secretary@nzccpts.co.nz, or via his contact details on the 'Contact Us' page of the NZCCPTS website (www.nzccpts.co.nz).

A brief description of the objectives and organization of the New Zealand Committee for the Co-ordination of Power and Telecommunication Systems Inc. is printed inside the back cover of this publication.

CONTENTS

1. Introduction

This publication provides guidance for investigating and mitigating cases of noise interference caused by power systems on telecommunication systems, so that resources can be applied effectively towards resolving problems.

Descriptions and explanations are included, of a range of disturbing current phenomena, which can arise in parts of the power system, and of conditions in which significant interference to the quality of performance of telecommunication systems can result. Suggestions are also included to assist with interpreting observations and measured data to assist investigators in achieving a clear understanding of the possible cause and source of the case under investigation so that the most appropriate mitigation can be pursued.

2. Background

Noise interference occurs in telecommunication systems located near electricity systems of all voltage levels, ranging from 230V standard low voltage networks on domestic, commercial and industrial locations, to high voltage distribution networks at 11kV and 33kV and extending up to the highest AC transmission voltage in New Zealand of 220kV AC, and the HVDC link.

The sources and causes of noise interference are many and varied. Therefore it is necessary for investigators to be aware of a wide range of power system disturbing conditions to be able to approach any reported case of noise interference in a careful and systematic manner.

Effective remedial action is dependant on a sound understanding of the cause and source of any reported noise interference.

3. Statutory Legislation and Standards

New Zealand Electricity Legislation does not directly specify any requirements on electricity networks or apparatus to limit the production of noise currents which could result in noise interference on nearby telecommunication systems.

However, Electricity Regulation 56 (in the 1997 Electricity Regulations) does prohibit the use of "any fittings or electrical appliance that unduly interferes with the satisfactory supply of ELECTRICITY to any other person, or unduly interferes with the operation of any fittings or electrical appliance. Compliance with the N.Z. Electrical Code of Practice for Harmonic Levels (NZECP 36) is deemed to be compliance with Electricity Regulation 56 in respect of interference from harmonics".

NZECP 36 'Harmonic Levels', and joint Australian New Zealand Standard AS/NZS 6100.3.6 'Assessment of emission limits for distorting loads in MV and HV power systems', define limiting values for power system voltages and currents at harmonic frequencies (and interharmonics in the case of AS/NZS 6100.3.6) primarily to prevent undue interference with the operation of any other electrical apparatus or equipment connected to the power system. NZECP 36 also includes limit values for "equivalent disturbing currents" for power system voltages of 66kV, 110kV and 220kV. These specifically limit the noise voltages that could be induced on nearby telecommunication lines and cables, but apply only at power system voltages of 66kV or higher.

Noise interference in telecommunication circuits occurs over a wide range of frequencies up to, and above 3kHz, with the greatest proportion of noise interference problems arising from electromagnetic coupling between 11kV and 33kV power systems and nearby telecommunication systems.

Among noise problems investigated by Telecom, in the 1990's, in only one case out of many were the NZECP 36 harmonic limits exceeded. Compliance with NZECP 36 is certainly no guarantee that noise problems on telecommunication circuits won't eventuate. So New Zealand Electricity Legislation and Electrical Standards are only of limited relevance in investigating and remedying noise interference problems in telecommunication systems.

However, Common Law rights still apply – both the Telecommunication Network Operators (TNOs) and affected telecommunications users can sue the relevant Electricity Company and/or electricity users(s) for any "undue interference".

4. Electromagnetic Interference to Telecommunication Systems

The following sections 4.1 to 4.4 are included to provide an understanding of the nature or characteristics of 'noise' on telecommunication systems, and of the mechanism of coupling between power and telecommunication systems which results in noise interference.

4.1 Tolerance of Noise by Telecommunication Users

In recent years Telecommunication Network Operators have been fielding a steadily increasing number of power noise complaints from their customers. This has been caused in part by the increasing levels of harmonic currents in the power HV networks generally, but it has also been aggravated by two trends:

(1) telecommunication customers expectations of a “quiet” telephone circuit have been steadily increasing for the last 20 years, and
(2) more and more fax machines and computers are being connected to telephone circuits.

Whereas in the past telecommunication customers might have been prepared to tolerate “bursts of noise” during their telephone conversation, now that these bursts of noise are making data transmission speeds frustratingly slow, and even dropping off transmissions, they are no longer acceptable.

4.2 Theory of Coupling

Interference originating in power systems which affects the quality of performance of telecommunication systems normally only occurs as a result of electromagnetic coupling between power system circuits and metallic telecommunication circuits. The degree of interference depends on a number of factors including:

- the physical spacing between the power and telecommunication systems
- the effective resistivity of the earth at the interfering frequency(ies)
- the frequency and amplitude of the interfering or disturbing current or combination of currents
- the level of electromagnetic shielding provided for the telecommunication circuits
- the extent to which the individual pairs of affected telecommunication conductors are well balanced
- the susceptibility of the telecommunications equipment to interference.

The following sections explain the relationships in detail and also explain the significance of psophometric weighting over the frequency range relevant to speech communication.

4.2.1 Induction Formula

The voltage induced between each conductor and earth, on ALL copper conductors in a telecommunication cable (or line), from a parallel power conductor, is given by

$$E_{ind} = C \times L \times I \times K \quad \text{volts}$$

Now

$$C = 2 \times \pi \times f \times 10^{-4} \times Log_e \left[1 + \left(\frac{6 \times 10^5 \times \rho}{s^2 \times f} \right) \right]$$

where

C = mutual impedance (or Coupling Factor) at frequency f, between the parallel power line and the telecommunication cable or line (in ohms per kilometer)

L = length of parallel (in kilometers)

I = power conductor current at frequency f (in amps)

K = shielding factor for telecommunication circuits at frequency f (this is always a value between 0 and 1)

ρ = effective earth resistivity at frequency f (in ohm-metres)

s = separation (in metres) between the telecommunication and power conductors

f = frequency of the interfering current (in Hertz)

It can be seen from the above formula that the mutual impedance C (and hence also the induced voltage E_{ind}) only has a very **muted** dependence on either the effective earth resistivity (ρ), or the separation between the power and telecommunication cables/lines (s). This is not widely appreciated. This is illustrated in the example below, which looks at the variation in C for different typical separations.

Example: For f = 800Hz and ρ = 300Ω-m

Location of HV Power Line	**Separation**	**C (Ω/km)**
In fields (i.e. cross country)	100m	1.6
Opposite side of road	17m	3.3
Same side of road	8m	4.1
Minimum separation in shared trench	0.45m	7.0

The level of induced voltage is **very** dependent on the magnitude of the disturbing current (I) and the length of parallel (L), and only slightly dependent on the separation (s) and effective earth resistivity (ρ)

The net induced voltage is the (vector) summation of the calculated induced voltages from ALL current carrying conductors.

The voltage, E_{ind}, induced between each conductor and earth, is known as the **LONGITUDINAL** induced voltage.

4.2.2 Balance of Telecommunication Circuits

The voltage that conveys the speech or data information on a telecommunication circuit is the voltage between the a-leg and b-leg of the telecommunication twisted pair (known as the **TRANSVERSE** voltage).

If the a-leg and b-leg of a twisted pair have identical electrical characteristics, then at the customer's telecommunication equipment the longitudinal (induced) voltage on each leg of the pair (relative to earth) will be exactly the same, resulting in a 0 volts transverse noise voltage (between the a-leg and the b-leg). However, in the REAL world, slight differences between the electrical characteristics of the a-leg and b-leg will exist, due to the cable manufacturing tolerances and installation processes, cable joints, etc. As a result, there will be a slight difference in the longitudinal voltages a-leg to earth and b-leg to earth, at the customer's telecommunication equipment, causing a **TRANSVERSE** noise voltage (a-leg to b-leg) to appear.

The "balance" of a telecommunication pair is a measure of how much of the longitudinal voltage (a-leg to earth and b-leg to earth) is "converted" into a transverse voltage (a-leg to b-leg). Balance is normally expressed in decibels (dB), and is calculated as follows:

$$\text{Balance} = 20 \log_{10} \left(\frac{V_L}{V_T} \right) \quad \text{dB}$$

where V_L = Longitudinal Voltage
V_T = Transverse Voltage (caused by longitudinal voltage V_L)

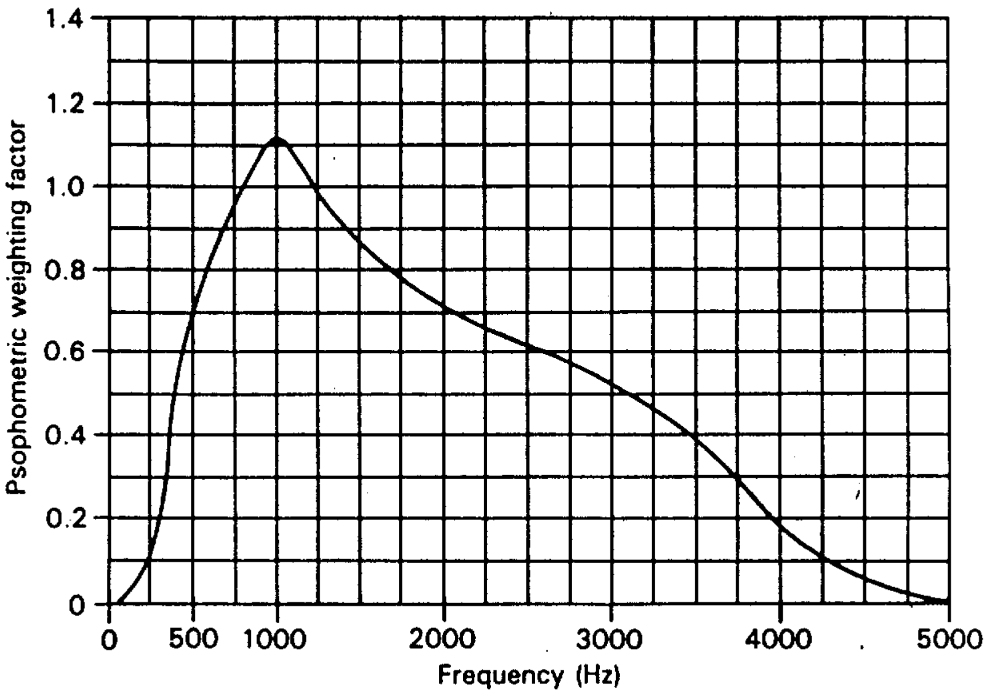
A telecommunication pair is considered to have **good balance** if its balance is > 60dB
(i.e. $V_T < 0.1\%$ of V_L).

Very high levels of longitudinal voltage (e.g. greater than 32Vrms) can cause **additional** major problems, even on telecommunication circuits with excellent balance, by driving the Telephone Exchange line card (or customers equipment electronics) that the cable circuit terminates on, into a non-linear **unbalanced** state.

The impact of a transverse voltage on a telecommunication circuit depends on its magnitude and frequency and the susceptibility of the service to interference.

4.2.3 Psophometric Frequency Weighting Curve

The effect of transverse noise voltages on a telephone service is not uniform over the audio frequency spectrum. The European telecommunications standards body, the International Telecommunication Union - Telephony (ITU-T) (formerly known as the CCITT), has attempted to address this by determining the following “Psophometric Frequency Weighting Curve”, which represents the (measured) sensitivity to audio frequencies of a “standard” human ear in combination with a “standard” telephone set.



Psophometric Weighting Curve for a Telephone Circuit

The psophometrically weighted voltage on a telecommunication line is the ROOT MEAN SQUARE sum of the products of the magnitude of each noise voltage (V_n) and the corresponding psophometric weighting factor (P_w), at each noise frequency (f_n).

i.e. $V_p = \sum_{f_n} [V_n(f_n) \times P_w(f_n)]$

So, as the frequency of the noise voltage increases from 100Hz to 4kHz, a number of opposing trends come into play

- the magnitude of harmonic currents tends to decrease
- the Coupling Factor (C) increases substantially
- the psophometric weighting factor (P_w) varies substantially

Example: for 17m separation and 300Ω-m earth resistivity

Frequency	C	P_w	C x P_w
50Hz	0.3	0.007	0.002
1kHz	4.0	1.1	4.4
4kHz	12.7	0.2	2.54

This is why the majority of power noise problems on telecommunication circuits occur in the 400Hz to 4kHz frequency band. This causes some measurement problems, since most power harmonic analysers only measure up to the 50th harmonic (i.e. 2.5kHz).

Note that the psophometric weighting curve only really applies to voice communications. Most voiceband data equipment, e.g. fax machines, computer modems, etc., have a FLAT frequency response across the 300Hz to 3.4kHz band (i.e. their Frequency Weighting Factor = 1.0 across the whole voice frequency band).

4.3 Allowable Noise Limits on Telecommunication Systems

Allowable noise limits are specified for both the transverse and longitudinal noise voltages as detailed in 4.3.1 and 4.3.2.

4.3.1 Transverse Noise Voltage

The ITU-T limit for the psophometric weighted transverse noise voltage, as measured at the customer premises across the telecommunication line terminated in its characteristic impedance (normally assumed to be 600Ω), is 0.5mV (= -64dBmp, or 26dBrnp).

4.3.2 Longitudinal Noise Voltage

The corresponding limit usually applied to the psophometric weighted longitudinal noise voltage, as measured at the end of a telecommunication line, between a-leg and earth and b-leg and earth (or between a-leg and b-leg combined together, and earth) is 500 millivolt
(= -4dBmp, or 86dBrnp).
[This is the minimum longitudinal voltage that could cause a telecommunication line with GOOD in-service balance (i.e. 60dB or better) to exceed the above transverse noise voltage limit.]

5. Causes and Nature of Disturbing Currents in Power Systems

Disturbing currents, that is, those currents other than the 50Hz fundamental current which cause interference by electromagnetic coupling to other metallic conductor systems are caused by:

- modification/deformation of the fundamental waveform for power flow or load control purposes
- injection/superimposition of currents of one or more frequencies into the AC network from apparatus connected to it
- addition of higher frequency currents as a result of internal network resonances, i.e. between inductances and capacitances within or connected to the network
- maloperation or incorrect operations of power system equipment such as transformers when magnetic saturation occurs

Disturbing current frequencies can extend from very low frequencies, in the order of a few hundred hertz, up to the kilohertz range. The component frequencies present in each interference case can often provide useful clues as to the type of process, apparatus, or condition which forms the source of the interference.

5.1 Sources of Noise Interference Currents

Low voltage urban networks, 11kV to 33kV distribution networks, and high voltage transmission networks of 66kV and above, can all give rise to noise problems. Each type of network exhibits a range of problems more commonly associated with that network than the other types. An outline of the commonly encountered interference sources for each type of network is set down in Subsections 5.1.1 to 5.1.3. More detailed information on some sources of interference is included in the Appendices for reference.

5.1.1 Sources in Low Voltage Networks

Because of the very limited lengths of 230/240V standard low voltage circuits, disturbing currents generated at the 230/400V level hardly ever cause any noise problems due to direct induction from the 230/400V conductors. They do, however, often cause problems by migrating up to the 11kV network level (at a reduced level), and there coupling onto the telecommunication network via the considerable lengths of parallel between the telecommunication network and the 11kV network (often many km).

The sources and characteristics of disturbing currents in the low voltage urban networks include:

Source	Disturbing current characteristics
motor speed controllers	odd order harmonics at higher frequencies sometimes above the 50th harmonic
switched mode power supplies	3rd order harmonics, and above 10kHz
fluorescent lights and high efficiency light bulbs	3rd or 5th order harmonics and above
personal computers	2nd order harmonics, but may also include some frequencies in the kHz range
building service transformer resonating with power- factor/ voltage correction capacitors	predominantly an odd or even order harmonic
ripple control	long bursts of a specific frequency in the 50Hz – 3kHz range

5.1.2 Sources in Distribution Voltage Networks

Most power noise problems on telecommunication circuits come from 11kV and 33kV lines because of the long and relatively close parallels which exist both in urban and rural areas between the power and telecommunication networks.

The sources and characteristics of disturbing currents in distribution networks include:

Source	Disturbing current characteristics
faulty connections in overhead power plant	broadband "hash" (i.e. noise across a wide frequency spectrum)*
unbalanced voltage (also 2 phase supplies to a single phase/phase to phase load)	broad range of frequencies. Some publications suggest total harmonic distortion increases 1% for every 1% voltage unbalance of a 3 phase system
resonance (between inductance of long feeders and voltage connection capacitors)	a specific frequency, either odd or even harmonic predominates
ripple control signals	long bursts of a specific frequency in the 500Hz – 3kHz range

* Such a situation can produce significant noise well before the faulty connection degrades to the point that it affects the operation of the power system.

5.1.3 Sources in Transmission Voltage Networks

The transmission network includes very long lines particularly at voltages of 220kV, and can exhibit phenomena such as standing waves which cannot occur on shorter lines. Also, noise currents in 66V and higher voltage lines tend to be greater in magnitude that noise currents in distribution lines. However, because 66kV and higher voltage lines normally travel cross country, while virtually all telecommunication lines and cables are situated in the road reserve, there are not many long and close parallels between transmission lines and telecommunication lines and cables.

The source and characteristics of distorting currents in high voltage transmission networks include:

Source	**Disturbing current characteristics**
resonance	specific odd or even order harmonic with significant zero sequence component*. Magnitude will vary as terminating load network impedance characteristics change with changes in load on local network
geomagnetic currents (has occurred, and is only likely to occur, in the Invercargill area)	even order harmonics generated by saturation of high voltage and transformers
HV load producing harmonic frequencies in range 11^{th} harmonic and above	standing wave occurs at end of a long line remote from source only when the terminating load is very small in relation to capacity of the line

* If the interfering frequency is a power system harmonic frequency, on a 3 phase transmission network, it is possible for the harmonic magnitude to be within the limit set in NZECP 36 but still cause interference if the zero sequence component is a significant part of the phase current.

5.1.4 Propagation of Disturbing Frequencies

Disturbing currents on the power system, particularly in the higher frequency ranges which are of most concern for telecommunication interference do not propagate easily through the power system. The leakage capacitances to ground, and the reactances within the various power system circuits provide some shunt filtering benefits.

There are some situations in which widespread problems can arise. Such a situation can occur if a very large disturbing current source is connected to a 'weak' power network at the end of long transmission lines of high impedance. In such a case there is a step-up effect as the disturbing currents flowing between the load and the distribution or transmission network (which are usually fixed in relation to the fundamental load current of the disturbing source) result in increasing disturbing current and voltage levels as they pass through the higher impedances of the network. Significant voltage distortion on the power system can result, causing harmonic currents to flow everywhere.

6. Investigation Procedure

Investigation of power system to telecommunication system interference involves six important steps:

i) establishing a detailed understanding of the nature and symptoms of each reported case, i.e.

- does the interference occur continuously, or at regular intervals or definable times (e.g.12 noon daily for 10 minutes) or does it occur at random intervals and for random durations
- what are the characteristics of the interference – a steady tone or a noise covering a spectrum of frequencies
- does it occur in a telecommunication system near a power system overhead transmission or distribution line uniformly along the length of the overhead line or near one end only

ii) identifying recent changes to equipment or circuits at the site, or in nearby network/s, e.g.

- what changes have been made to the telecommunication network
- has new equipment been installed, or old equipment removed from service in the power network

iii) obtaining measurements (and making observations) over a period of time to cover a variety of conditions (the local power company and telecommunication network operators working together) e.g.

- obtain records of noise levels and frequency characteristics on the telecommunication system
- recording power network changes, load levels, times of switching and locations, connection/disconnection of power factor capacitor installations

iv) evaluating/analyzing the recorded data, e.g.

- consider the nature of the interference. If specific order harmonics predominate, this gives some idea of possible sources
- identify inter-relationships such as presence of interference when certain power network configurations occur, or when specific equipment is in or out of service
- identifying random relationships, i.e. interference starts/increases co-incident with several independent power network events
- where initial data/records/observations do not lead to satisfactory analysis more sophisticated measurement and analysis may be necessary – see Section 6.3.

v) determining solutions (power company and telecommunication network operator working together)

- solutions should consider both the cause and the susceptibility of the telecommunication network, as the situation may, for example, have identified an old telecommunication design/installation needing upgrading to current standard being affected by a low level power system source.

vi) evaluating solutions by trial or test e.g.

- where the cause is identified, then the effectiveness of the proposed modifications can be checked
- where the cause is network resonance, testing de-tuning by re-configuring the power network can be worthwhile

6.1 Difficulties Experienced in Resolving Noise Problems

The following practical difficulties have been commonly experienced when investigating noise problems:

- identifying the noise type
- locating the source of the noise (especially if the noise is intermittent)
- time pressures on TNO (Telecommunication Network Operator) and Power Company fault staff to quickly resolve problems which may be quite complex
- skill limits of local TNO (and Power Company) fault staff
- lack of clear legislation specifying noise limits, and who is responsible for policing these.

6.2 Methods of Measuring Noise on Telecommunication Circuits

The method of measurement differs between that required for longitudinal noise voltage and that required for transverse noise voltage, as detailed in 6.2.1 and 6.2.2.

6.2.1 Measurement of Longitudinal Noise Voltage

The weighted induced longitudinal voltage can be measured by:

- connecting both wires of the line to earth at the telephone exchange end of the line, and
- using a high impedance psophometrically weighted rms voltage measuring instrument to measure the weighted longitudinal voltage between the line and local earth at the telephone instrument termination of the line .

Note - this measurement is best taken at the customers end of the telecommunication line. It is usually only of limited use when taken at the telephone exchange end of the line.

6.2.2 Measurement of Transverse Noise Voltage

Measure the transverse psophometric voltage on a line as follows:

- Set up a call to a “quiet” termination.
- Measure the psophometrically weighted transverse noise voltage using an instrument that terminates the line (typically on an internal 600Ω resistor).

6.3 Measurement of Noise Currents on Power Networks

Because the frequencies of the disturbing currents which can cause 'noise' interference extend over a wide spectrum it is necessary to choose measuring equipment likely to suit the portion of the frequency spectrum considered most likely to be relevant to each specific investigation. Telecom N.Z. Ltd. has equipment suitable for measuring frequencies up to around 40kHz, while Transpower and Canterbury University have equipment more suited to frequencies up to 2500Hz. Sections 6.3.1 and 6.3.2 describe this equipment. Portable 'harmonic analyzers' have some limitations for measuring power 'noise' currents and this is explained in Section 6.3.3.

6.3.1 Telecom N.Z. Equipment

To assist in resolving power noise problems on Telecom lines, Telecom NZ Ltd has put together the following set of equipment:

(1) a hot stick mountable CT with an analogue output, isolated from the CT via a fibre optic cable, with a 3 kHz bandwidth and rated to 40kV,

(2) a hot stick mountable VT with an analogue output, isolated from the VT via a fibre optic cable, with a 3 kHz bandwidth and rated to 40kV,

(3) a portable spectrum analyser (with a 40kHz bandwidth and a 66dB (1:2000 voltage ratio) dynamic range).

This equipment is available for use in joint Telecom/Power Company power line noise surveys, with the Power Company providing the hot stick and hot stick operator, and Telecom providing the measuring equipment and spectrum analyser operator.

6.3.2 Transpower N.Z. Ltd and Canterbury University Equipment

The most comprehensive measuring and recording equipment, for frequencies up to 2500Hz, capable of assembling data from several locations simultaneously is the CHART (Continuous Harmonic Measurement in Real Time) recording system manufactured by Canterbury University Department of Electrical Engineering.

Canterbury University also has a three phase harmonic penetration programme, HARMAC, for computer simulation of transmission and distribution networks, which is suitable for studying network conditions and assessing prospective solutions for reducing the magnitude of interfering sources. They have a comprehensive South Island harmonic model for this software which has been used for a variety of studies.

Transpower New Zealand Ltd. holds two CHART recorders, the HARMAC software with the South Island model, and Syslib, a new in-house harmonic analysis software library customized for the New Zealand power system. A North Island three-phase harmonic model down to the Transpower asset boundary has been developed for Syslib.

Enquiries for assistance with field measurements using these recorders and/or assistance with investigations and analysis of interference problems can be made direct to either of these organizations.

6.3.3 Standard Power Industry Harmonic Analysers

Generally Power Industry harmonic analysers are not very suited to measuring power "noise" currents, because:

- virtually all harmonic analysers only measure up to the 50^{th} harmonic (i.e. 2.5kHz), while many power noise problems on telecommunication circuits are at frequencies up to 4kHz, and sometimes as high as 10kHz
- most harmonic analysers have an 8 bit Analogue to Digital (A/D) converter, which means they can only measure currents down to 1/256th of the largest current on the power line (normally the fundamental 50Hz current). However much lower currents than this, particularly in the 500Hz to 4kHz frequency band, can cause major problems.

7. Key Points for Analyses

(a) in most cases the cause will be close to the location of the reported problem
(b) the characteristics of the interfering signals may give some idea of the nature of the originating source
(c) resonance, or 'near resonant' conditions can be initiated by a variety of sources ranging from the addition/subtraction of network loads to the opening/closing of network switchgear
(d) long power network transmission or distribution lines terminated in transformer substations can support standing waves
(e) harmonic frequencies do not propagate easily over long distances if standing wave conditions are not present
(f) old telecommunication networks may not be well balanced
(g) standing wave conditions involve current nodes and anti nodes at quarter wavelength intervals and consequently give rise to interference locations spaced half-wavelength distances apart
(h) power system resonance may involve high levels of zero sequence currents and result in 3 times the interference caused by the same currents in a single phase circuit
(i) painstaking care, and perseverance may be necessary to achieve a sound solution
(j) expertise and good quality measuring/recording systems are available

8. Noise Mitigation

The ideal solutions for eliminating or minimizing noise interference are either to deal with the source of the disturbance, or to increase the separation between the relevant power and telecommunication circuits.

In many situations, the likelihood of noise interference occurring is not foreseen, and the relevant installation is completed before any problem is encountered. Mitigation, rather than avoidance of the problem, is often then the most economical approach that can be taken.

8.1 Options for Reducing Noise Interference Currents in the Power System

The options available for reducing the magnitude of interfering currents include:

- filtering close to the source — This is suitable where specific noise current frequencies, or a band of higher order noise current frequencies, is involved
- transfer of the disturbing load to another part of the power network — This may be suitable where the cause is resonance, as transferring the load may de-tune the resonant circuit
- adjust the value of the power factor/voltage correction capacitors — This may be an option where a distribution line, or a building power system, resonance is involved

8.2 Options Within the TNO Network for Mitigating Noise

The following options can be applied within the telecommunication network to mitigate noise:

(1) If the balance of the telecommunication circuit is poor, this can be improved by:
- repairs to the cable circuit
- replacement of poorly balanced cable
- alternative means of providing service (see (4) below).

(2) Noise chokes can be installed at the appropriate location(s) in the telecommunication cable circuit. This typically only provides of the order of 6dB improvement in noise levels, so it is usually only useful for mitigating mild noise problems.

(3) Bonding the barrier sheath or lead sheath (typically found in urban cables only - barrier sheath is like tin foil) and/or spare copper pairs in the cable to earth, will improve the screening of the cable, typically reducing the resultant noise level on the cable conductors by about 6dB.

Again, this is usually only useful for mitigating mild noise problems, and requires low resistance earth connections at each end to be effective. Specially made screened cables can provide much more effective screening, but these have to be specially designed and manufactured, and are very expensive. Installing cables in iron pipe can also provide pretty effective screening, but this is usually very expensive, unless only a relatively short distance is involved (e.g. at a crossing under a line carrying very high noise currents).

(4) Shortening (or eliminating) the length of copper (voice frequency band) conductor in parallel with the noisy power line. This can be done by:

(i) using a derived circuit system over part (or all) of this parallel length (e.g. 0+2's),
(ii) laying new cable by an alternate route,
(iii) converting the circuit(s) to a Subscribers Multiplex cabinet fed by fibre optic cable over the parallel length,
(iv) converting the circuit(s) to radio.

Options (ii), (iii) and (iv) are usually very expensive, and option (i) is often not technically feasible.

9. References

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APPENDIX A

HARMONIC FREQUENCIES

A.1 Characteristic Features of the Harmonic Frequencies

A harmonic is a sinusoidal component of a periodic wave or quality have a frequency that is a multiple of the fundamental frequency (ref. The New IEEE Standard Dictionary of Electrical and Electronic Terms).

For the 50Hz power system, all frequencies which are not multiples of 50Hz are described as inter-harmonics, i.e. they fall in the intervals between harmonics.

Generally, odd-order harmonics exist in greater magnitude than even-order harmonics. Inter-harmonic frequencies are generally low magnitude frequencies unless deliberately injected into the 50Hz system. When the load involves control features which modify the load current waveform, then both voltage and current harmonics will exist. If the harmonic current components are determined by the characteristics of the load, then the magnitude of the voltage harmonics are determined by the impedances of the parts of the network the load current passes.

Many harmonic frequencies are characteristic of the originating source.

Rectifiers/inverter installations produce odd-order harmonics on the AC network. For 3 phase systems the frequencies produced are of the order of np±1 where n represents any integer and p is the rectifier pulse number. A 6-pulse rectifier produces harmonics of orders 5, 7, 11, 13 and son on, the amplitudes decreasing with increasing harmonic order. For a 12 pulse rectifier the lowest harmonic which will also be the highest amplitude AC harmonic frequency produced will be the 11th harmonic and for a 24 pulse rectifier it will be 23rd harmonic.

Fluorescent lighting systems produce odd-order harmonic frequencies commencing with 3rd order harmonics. Magnetic ballast type fluorescent lighting installations produce 3rd harmonic currents of around 20%, and 5th harmonic currents of around 10%, of the magnitude of the fundamental current. Electronic fluorescent lighting installations can produce 3rd harmonic currents of similar magnitude to the fundamental current. As a consequence of high 3rd harmonic currents being produced in lighting installations, there will be very high neutral currents and high zero sequence currents in the associated supply transformers.

DC currents flowing into transformer neutral connections cause a DC flux bias in the transformer core, leading to asymmetric saturation and generation of new even order harmonics, particularly the second harmonic. This type of DC current (ground mode) is also caused by HVDC links under some conditions, and can only effect grounded star type transformer connections. Metallic mode DC current flows between phases and can therefore saturate all common types of transformer connection. This type of DC current is less likely to exist in the system, and is sometimes caused by three phase power electronic devices with asymmetric firing errors. Zero sequence currents other than 'DC' do not cause transformer saturation.

A.1.1 Geomagnetic Interfering Currents

Variations in the earths magnetic field causes potential gradients across the ground surface. These are greatest in latitudes nearer the earth's magnetic poles and the gradients usually lie in an east-west direction. Where long transmission networks run in an east-west direction with grounded transformer neutrals many kms apart, the geomagnetic potential gradient will cause quasi (slowly varying) dc currents to flow between the grounded transformer neutrals and along the AC lines. At times of peak auroral activity dc currents in the order of 12A to 15A have been measured flowing between Manapouri and Invercargill via the 220kV ac network.

A.2 Significance of Phase Sequence

Harmonic frequencies may be present in both 3 phase and single phase systems as
either positive, negative or zero sequence currents and voltages.

3 phase rectifiers/inverters produce harmonic currents with the following phase sequences:

Harmonic Order	Sequence
2	-
3	0
4	+
5	-
6	0
7	+
8	-
9	0
10	+
11	-
12	0
13	+
14	-
15	0

(note: depending on the form of rectifier/inverter, only some of the above harmonics may actually be produced).

The resulting harmonic currents flowing in the network will predominantly follow the above pattern, however in general harmonic currents can be of any sequence due to sequence transformation by transmission lines.

Negative sequence currents cause a counter rotating field, in motors, generators, induction meters, and protection relays, if negative sequence filtering is not installed. This inevitably results in reduced efficiencies in rotating plant, and the slowing or under recording by induction type energy metering. High levels of negative sequence currents can result in incorrect protection relay operations.

Zero sequence currents are significant for telephone interference occurring in telecommunication circuits which are located near 3 phase power lines. The electromagnetic fields caused by the zero sequence currents in each phase actually add together, and the interfering effect to the nearly telecommunication circuit is effectively 3 times that of the individual zero sequence phase component.

Zero sequence currents arise in 3 phase networks when either unbalanced phase voltages exist on a network where the phase impedances are balances, or the phase voltages are balanced while the phase impedances are unbalanced.

APPENDIX B

STANDING WAVE PHENOMENA

Where a transmission or distribution line is long in comparison to the wave length of the signal, then there is a possibility of standing wave conditions arising. For this to occur, the line length will be close to either one quarter wavelength of the signal frequency, or a multiple of this, and a substantial change in impedance must exist at the far end of the line, either as an open circuit or as a transformer termination.

The quarter wavelength corresponding to various harmonic frequencies can be determined from the following:

$$\text{quarter wavelength at harmonic frequency} = \frac{6000km}{4n}$$

where n = harmonic number

and the fundamental 50Hz wavelength = 6000 km

A selection of quarter wavelengths for more commonly experienced harmonic frequencies are:

harmonic number	frequency (Hz)	quarter wavelength (km)
5	250	300
11	550	136
13	650	115
23	1150	65
25	1250	60
49	2450	30

Standing waves are more likely to develop on higher voltage systems where longer lines are common.

Where a standing wave is established, current and voltage nodes will occur alternately at quarter wavelength intervals. The relationship between the nodal maximums is expressed by:

$$V_{max} = I_{max} \times Z_o$$

Where V_{max} and I_{max} are the voltage and current values at the nodal maximums, and Z_o is the characteristic impedance of the line.

A transmission line with a length close to a multiple of a harmonic quarter wavelength can sustain a standing wave as a result of the effect of the terminating network or equipment impedances on the line impedance.

Telecommunications interference due to standing wave effects has been observed in line sections as short as 15 km. This particular case was at the 49^{th} harmonic, and was caused by the current maximum of an existing standing wave being moved when another line was decommissioned.

APPENDIX C

RESONANCE

Resonance occurs when the inductive reactance and the capacitive reactance in adjacent elements, or within the same circuit, are equal. Both series circuits and parallel circuits can be resonant. irrespective of whether the resonant circuit is series or parallel, the resonant frequency.

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where f = frequency
L = inductance in henries
C = capacitance in Farads

The addition of a capacitor can give rise to resonance with the inductance of the network to which it is connected. And indication of the likelihood of resonance conditions can be obtained using the following approximation:

$$n = \sqrt{\frac{MVA(sc)}{MVA(cap)}}$$

where n = harmonic number

MVA (sc) = short circuit duty of the network at the point of connection of the capacitor (in MVA)

MVA (cap) = MVA_r rating of the capacitor bank at 50Hz

For example, a 32 MVA capacitor bank is connected to a busbar where the short circuit duty is 2,600 MVA, then there is a possibility of resonance at harmonic number

$$n = \sqrt{\frac{2600}{32}}$$

$$= 9$$

that is, resonance at 450Hz is likely.

When it is proposed to add capacitors at the end of a long 11kV (or 33kV) distribution feeder for voltage correction purposes, the likelihood of encountering resonance should always be checked. A near resonant condition can exist without resonance occurring until changes in the loads connected to that network modify the overall capacitance or inductance sufficiently to initiate the production of the resonant frequency.

A common cause of resonance is the installation of power factor correction capacitors in buildings where the capacitors resonate with the inductances in the building local supply transformer. Interference to telecommunications and computer or data signalling systems within the building may result.

APPENDIX D

PROPAGATION OF DISTURBING FREQUENCIES

Loads or load control systems which cause harmonic currents are normally constant current sources. That means that the harmonic current amplitudes are fixed in relation to the fundamental current drawn by the load, and the harmonic current amplitudes do not change unless the control system or the characteristics of the load changes and thereby sets a new set of fixed current relationships.

The harmonic currents associated with the fundamental load current pass through the same impedances of the network or network which the fundamental current passes, unless there is a more suitable impedance path (parallel paths) for the harmonic currents to flow through.

This means that, when looking outwards into the network from the load the harmonic voltages appearing at various points in the network will be determined by the impedances the harmonic currents pass to supply the load.

A harmonic producing load connected to a low impedance busbar, will result in corresponding low harmonic voltages on that busbar, but where the load current is supplied via several high impedance overhead lines to the busbar, then higher harmonic voltage levels may be established as a consequence on those lines.

This apparent step in harmonic voltage levels is a common consequence of connecting a harmonic producing load onto a lower voltage low impedance network.

Where a number of high impedance lines supply a busbar, the busbar impedance will be much lower than the individual line impedances, but the percentage harmonic voltage levels on the individual lines may not be much different to that on the busbar because of the subdivision of the harmonic currents between the individual lines.

In high voltage transmission networks, e.g. 110kV and 220kV the relatively high characteristic impedances of those networks require a high harmonic voltage to cause any significant harmonic current to flow through the network. NZECP 36 sets a harmonic voltage limit of 0.3% for 23rd harmonics and above, on networks of 66kV to 220kV. This corresponds to a harmonic phase voltage of 381 volts, at 220kV, and therefore in a network with a characteristic impedance of around 400 ohms per phase the maximum harmonic current theoretically possible as a consequence will be less than 1.0A, and in practice even less.

Experience so far shows that frequencies above about 17th harmonic do not propagate very well in high voltage transmission systems unless standing wave conditions exist.

APPENDIX E

NETWORK IMPEDANCES

At low voltage levels of 33kV and below, the impedances of the networks are largely determined by the loads, as distribution lines are relatively short, and their capacitances are also low.

Long distance transmission circuits of 66kV and above, particularly at the highest voltage level of 220kV, are often long enough to support standing waves as described in Section 4.3. In general transmission circuits have relatively high impedances at harmonic frequencies.

The characteristic circuit impedances for 220kV and 110kV grid transmission lines are in the order of –

Simplex conductor, single circuit	- approx. 400 ± 20 ohms
Simplex conductor double circuit	- approx. 0.9 x 400 ± 20 ohms
Duplex conductor single circuit	- approx. 0.75 x 400 ± 20 ohms
Duplex conductor double circuit	- approx. 0.9 x 400 ± 20 ohms

Transmission cables, both underground and submarine, have characteristic impedances in the order of 30 ohms or less, and as they also present a very large capacitance value to ground, transmission cables have the effect of shunting higher order harmonic frequencies to ground.