Load control frequency injection cell structure-borne noise attenuation

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ABSTRACT

Zone substations are located at various strategic locations throughout the electricity network in Australia. These substations typically include several significant noise sources, transformers being the most common “problem” source. Changing consumer usage and increasing load demand requires ongoing augmentation of substations to keep pace with the changing requirements. Increasing capacity combined with new electrical technology introduces potential new noise sources to be assessed and addressed. Recent projects have seen capacitor and load control frequency injection (LCFI) cells causing significant noise levels on and off site for substations. The cells are used by energy authorities to control the hours of operation of equipment to reduce peak electrical loads on the network for various devices such as domestic hot water systems. The LCFI cells turn equipment on and off by sending signals (pulses) through the electrical system. This paper discusses the noise and vibration levels generated by a newly installed LCFI cell at a zone substation. The 80kVA, 283Hz LCFI cell was located in a masonry control room, and generated noise levels of 94dB(A) within the frequency injection room. This resulted in unsuitably high noise levels for staff elsewhere in the building. Analysis of the situation indicated that the noise was primarily structure-borne, and that a combination of vibration and noise control treatments would be required to adequately attenuate the noise. The installed treatments achieved a significant noise reduction for the building occupants and the results of the noise and vibration control treatments are presented in this paper. The information gathered will assist in addressing noise from similar LCFI cells at other zone substations in the electricity network, to protect the health and amenity of substation staff and nearby residents.

INTRODUCTION

A new zone substation was to be one of the first to have a new type of LCFI cell installed as part of a network upgrade. Immediately after installation, it was noted that the new units produced significant noise while sending the signal through the electrical system.

The LCFI cell was located in the Frequency Injection Room (FIR) adjacent an office area and switch room in the new control building (refer Figure 1). Operation of the LCFI cell caused concerns in the adjacent office and raised concerns for other units to be installed in several zone substations in residential areas. The control building had a suspended concrete slab floor, concrete block internal walls, brick external walls, and firerated plasterboard ceiling (3 x 16mm firerated plasterboard). The FIR was accessed via doors to the switch room and had a vent with fire damper (nominally 0.8m square) through the outside wall. Noise from operation of the FIU was clearly audible in the adjacent store/ office.

In order to address the noise issues, monitoring was undertaken to quantify the existing LCFI cell noise levels and to enable suitable noise and vibration control treatments to be designed. Following installation the effectiveness of the treatments was quantified by measuring the resultant noise reduction. This report outlines the methodology and results of this monitoring.

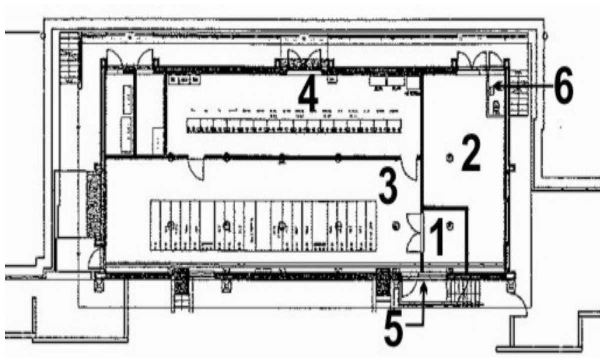

Figure 1. Plan view of substation control building (1. Frequency injection room (FIR), 2. Store/ office, 3. Switchroom, 4. Control room, 5. Landing, 6. WC, Toilet)

LCFI CELL ELEMENTS AND OPERATION

The 80kVA LCFI cell consists of 3 x capacitors, 3 x inductors and an isolating transformer. The cell under consideration sends a series of pulses in a batch around 40 times per day to control loads on various equipment in the area. Each pulse lasts for 6.6 seconds, and comprises 1 start tone + 5 signal tones. The pulses have a signal frequency of 283Hz (which is lower than other LCFI cells), and a batch lasts for 6.6 seconds up to 66 seconds. Usually there is a pause of 10 minutes or more between batches, to allow the LCFI cell to cool.

Noise is generated in electrical equipment due to magnetostriction (change in dimensions when subjected to a change of flux) and vibrations in windings due to pulsating forces acting on the mechanical conductors. At the normal frequency of electricity (50Hz), the sound produced is twice the exciting frequency (100Hz). The 283Hz load control frequency signal is sent as a smaller sinusoidal signal superimposed on the 50Hz electrical power sinusoidal signal. Therefore, the noise generated due to magnetostriction and vibrations when the load control signal is being transmitted, becomes greater in amplitude and includes 566Hz (2 x signal of 283Hz). When the load control signal is not being transmitted, the system has a low frequency hum characteristic of many electrical systems (eg. transformers). When the load control signal is being transmitted and superimposed on the normal electrical signal, the tone of the pulses sounds like a mid-frequency horn. The noise and vibration is caused by the change in flux density in the LCFI cell as the signal is sent.

Figure 2 shows the LCFI cell inside the FIR as seen through the open doors to the room. The capacitors and coils are supported on ‘C’ section beams, with insulators between the active components and supporting structure. The isolating transformer sits on legs mounted directly onto the concrete floor.

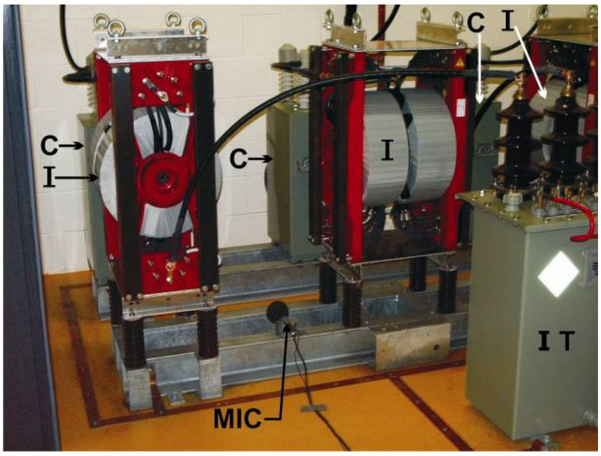

Figure 2. LCFI cell equipment in FIR room
(Isolating Transformer (IT), Inductors (I) centre row,
Capacitors (C) row behind inductors, Microphone (MIC))

Power cables associated with the LCFI cell equipment were mounted directly on the rear wall (common wall to the office) of the FIR as shown in Figure 3.

Figure 3. LCFI cell power cables mounted on FIR wall

SAFETY CONSIDERATIONS

When working on zone substations safety is a critical element of all work procedures as relatively standard work methods for non-electrical sites need to be modified to avoid the possibility of electrocution. A safety risk assessment was undertaken independently prior to arriving on site and reviewed again whilst on site to ensure all staff (both ERM and client) working on the noise and vibration measurements had a clear understanding of the hazards. The risk assessment involved identifying potential safety hazards, and agreeing on methods to eliminate or reduce the risks to an acceptable level. For example, the doors to the FIR were required to be open for some measurements, and the aluminium tripods were located at sufficient distance from the LCFI cell equipment so that if the tripod fell towards the FIR, it would not cause the equipment to arc.

When measurements were taken inside the FIR, the microphone and accelerometer were located on the ‘C’ section steel support beams below the equipment insulators (the microphone can be seen in Figure 2 mounted on the inductor ‘C’ section). For safety reasons the microphone and accelerometer were not able to be located higher in the room. The LCFI cell had to be de-energised and isolated prior to entering the FIR to install the microphone and accelerometer. ERM staff only entered the FIR after the client’s trained electrical staff had entered the room. When the LCFI cell was re-energised, all staff left the FIR and switchroom area, and the sound level meter and vibration analyser were not touched for several minutes to confirm no electrical charge was conducted via the microphone and accelerometer cables.

APPROACH

Noise and vibration measurements were undertaken at various locations inside and outside the FIU room to quantify the extent of the emissions.

Noise and vibration measurements were taken at the majority of locations with the LCFI cell de-energised, energised, and operational (i.e. sending pulses). This ensured that all operating modes were captured, and that spurious noise and vibration sources could be filtered out of the resultant data.

Measurements were taken during a test batch lasting around 30 seconds, comprising several pulses. During the tests, noise levels were recorded for 20 seconds, and vibration levels were recorded for 10 seconds. Instrumentation used for the measurements included: Rion NA27 Type 1 precision integrating sound level meter, Svan 912AE vibration analyser with Wilcoxon accelerometer, and Brüel & Kjær Type 4230 Sound Level Calibrator.

INITIAL MEASUREMENTS

Vibration

Initial measurements were undertaken to gauge the extent of the noise problem. Figure 4 shows the FIR vibration level spectrum in one third octave bands with the LCFI cell operational and energised. Measurements showed significant vibration levels in the 50Hz and 315Hz third octave bands when the LCFI cell was operational (ie. sending signal). The 315Hz band contains the injection frequency of 283Hz. Vibration was also present to a lesser extent from 400Hz up to 2kHz. The initial measurement was taken in the vertical plane with the accelerometer located on the 'C' section beam directly below one of the inductor coils.

It was found that when the LCFI cell was only energised (i.e. not operational), the vibration 1/3 octave band components at 315Hz and above were significantly reduced. The vibration level at 50Hz was also approximately halved (0.037 mm/s compared with 0.083 mm/s). While the 50Hz vibration level appeared significant, it was expected that the A-weighted noise level spectrum would show less 50Hz energy and highlight the mid-frequency noise levels.

Noise and vibration measurements and on-site observations indicated that the noise was structure-borne (ie. vibration entering the structure being re-radiated as noise in other parts of the building). It was noted that noise from the LCFI cell was clearly audible not only in the office, but in the toilet (two concrete block walls removed from the FIR), and in the external structure of the building. It was expected that the inductors and isolating transformer were the main sources of noise and vibration, although as individual LCFI cell components must operate simultaneously, detailed monitoring of each individual item was not possible.

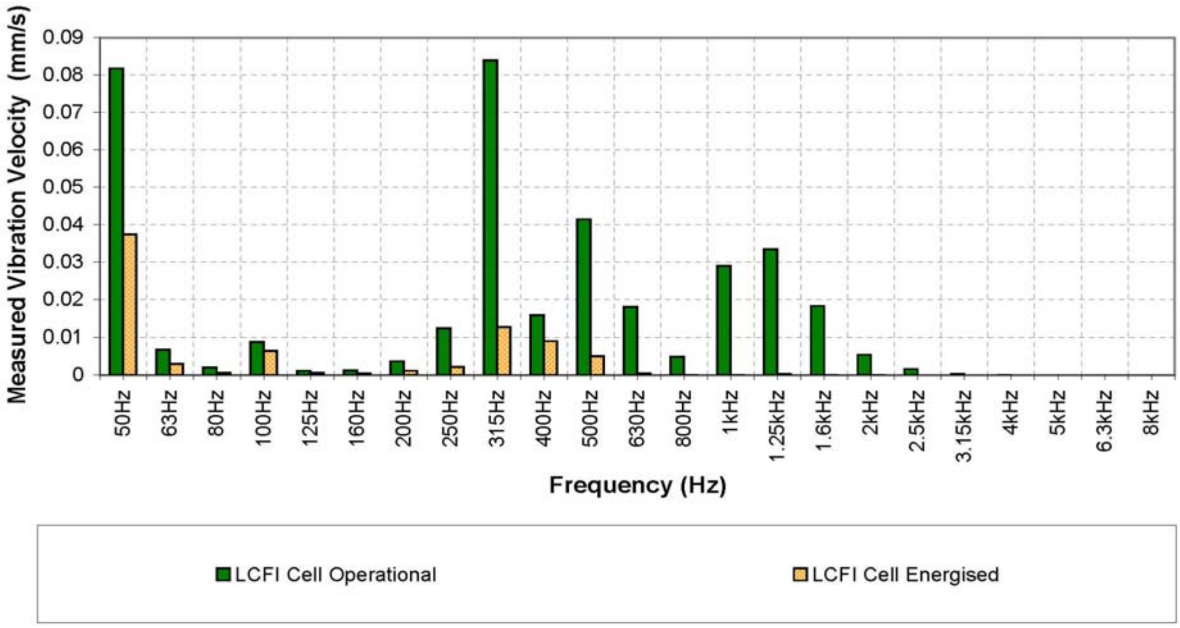

Figure 4. LCFI cell vibration levels in FIR

Noise

A noise level during operation of the LCFI cell of 65dB(A) was measured in the adjacent office, from noise and vibration radiating through the concrete block wall and firerated plasterboard ceiling. Noise level calculations were undertaken based on the measured levels inside the FIR, to determine the relative contributions from structure-borne noise and air-borne noise. Air-borne noise is sound which is radiated from the equipment via the air through walls, ceilings, doors etc. to arrive at the receiver. Structure-borne noise is caused by vibration from the equipment which enters the structure and is then re-radiated into a room by the walls, ceilings, doors etc. in that room. It has the ability to travel further in a building than air-borne noise.

The calculations taking into account the transmission loss of the wall and ceiling, indicated that the level in the office during pulses should be around 48-50 dB(A) if the noise was air-borne. However the measured level in the office was 65 dB(A), indicating that the noise experienced in the office was primarily structure-borne. Hence to achieve a significant improvement in noise levels, the equipment would require a high level of vibration isolation.

NOISE & VIBRATION TREATMENTS

Proposed Treatments

Three approaches to noise reduction were proposed:

- Reduction of signal strength to reduce the amount of energy being radiated into the building;
- Installation of vibration isolation mounts between the equipment and the building structure to control vibration energy entering the building and re-radiating as structure-borne noise; and
- Installation of acoustic insulation to the walls and ceiling of the FIR to reduce the reverberant noise levels in the room and lower the overall noise level.

Initial material selections were made by the electrical staff responsible for installing the equipment, and these were reviewed in light of the noise and vibration requirements.

Priorities for Treatments

It is always important to reduce the noise level at the source wherever possible as a first point of noise reduction. In this case, the electrical engineers suggested reducing the signal strength to gauge the effect on noise levels.

Based on the initial measurements and calculations, it was determined that treatment priority should be given to installation of vibration isolation elements, to attenuate the structure-borne noise. Following this the air-borne noise attenuation treatments could be added.

Reduction of Signal Strength

The Substation usually injects at 360Volts signal strength, however there was discussion that remote receivers may operate satisfactorily on a reduced signal. Hence this was tested on site to determine the level of noise reduction that could be achieved.

Vibration Isolation

Analysis of the isolators initially proposed showed they were too rigid and would not provide sufficient isolation. Calculations were undertaken using equations (1) to (4) based on supplied weights and mounting information, and the isolators were reselected to provide > 95% dynamic vibration isolation efficiency at 50Hz and above.

$$Fn = \frac{1}{2\pi}\sqrt{\frac{g}{d}} \tag{1}$$

$$Fd = DF \times Fn \tag{2}$$

$$T = \left| \frac{1}{1 - \left(Fs/Fd \right)^2} \right| \tag{3}$$

$$I\% = (1 - T) \times 100 \tag{4}$$

Where: Fn = Natural frequency; g = 9810mm/s^2 ; d = static deflection in mm under the weight of the equipment; Fd = dynamic frequency; DF = dynamic factor for the isolator; T = transmissibility; Fs = driving frequency in Hz; I% = isolation efficiency in percentage.

These isolators were "softer" in order to achieve the required isolation, however as there is no mechanical excitation of the LCFI cell equipment (ie. unlike a pump or compressor with moving parts), this was considered acceptable. As a result of the "softer" isolators the equipment effectively "floats" on rubber (ie. will move if pushed). As the relative contribution of the individual LCFI cell elements could not be determined (as all elements run simultaneously), it was decided that isolators would be selected and installed for all items that may transmit vibration into the building structure.

In discussion with the vibration isolation suppliers, the following elements were selected based on the load data provided and discussions on mounting arrangement with the electrical staff:

- Isolating transformer (270kg) - 4 off, double deflection rubber mounts (max. load 400kg);
- Inductors (coils) (212kg) - 12 off, medium stud mounts (max. load 312kg);
- Capacitors (56kg) - 12 off, soft stud mounts (max. load 64kg);
- Cable Unistrut support (9kg est.) - 2 off, double deflection rubber mounts (max. shear load 10kg); and
- Cable bracket (27kg est.) - 3 off, double deflection mounts (max. shear load 33kg).

The locations of the isolators are shown in Figure 5.

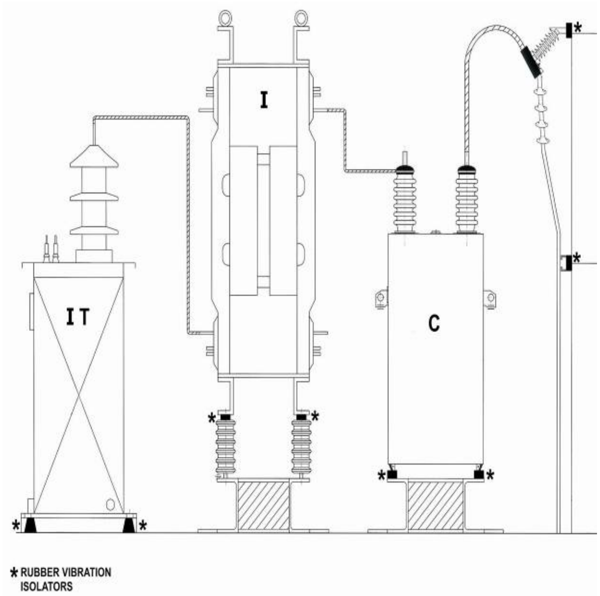

Figure 5. LCFI cell equipment vibration isolator locations (Isolating transformer (IT), Inductors (I), Capacitors (C))

Isolator connection details were as follows:

- Double deflection rubber mounts had M10 and M8 threaded female;
- Stud mounts had M10 and M8 threaded male extending each side of rubber element;
- The double deflection rubber isolators could be mounted under the transformer using a steel plate to spread the load across the two edges of the existing channel section base. Alternatively on site, it was found that the isolators could fit inside the channel section while still maintaining clearance between the floor and the channel section, which proved to be an easier installation solution. These isolators were bolted to the transformer, but were not bolted to the floor as the weight of the transformer combined with the friction grip of the rubber isolators provided a stable system.
- Flexible earth straps were used to connect the equipment to the earth system (in lieu of the previous solid copper elements).

Figures 6, 7 and 8 show the isolators installed on the LCFI cell equipment.

Figure 6. Isolating Transformer with vibration isolators installed

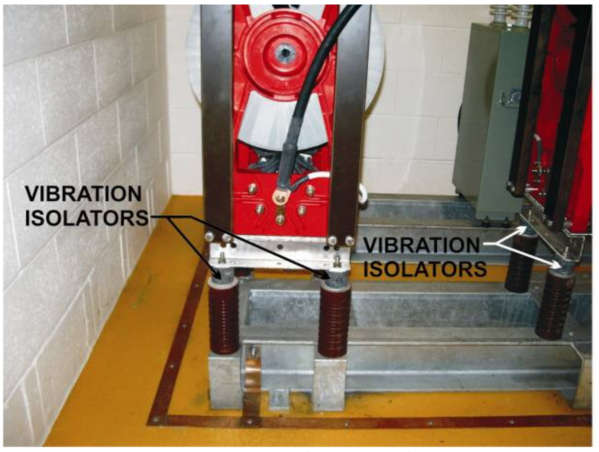

Figure 7. Inductors with vibration isolators installed

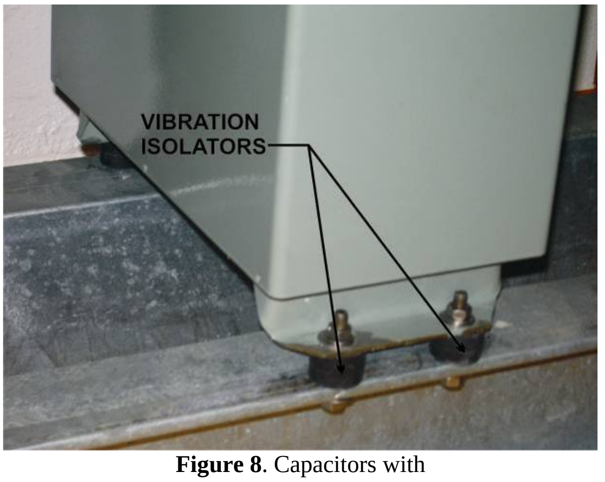

Figure 8. Capacitors with vibration isolators installed

Noise Control

Airborne noise could be reduced by increasing the transmission loss of the common wall between the FIR and the office, and by reducing the reverberant noise levels inside the FIR. Given the reverberant nature of the FIR with all hard concrete and plasterboard finishes, it was agreed that treatment of the reverberant field was appropriate. Calculations indicated that the installation of acoustic insulation to two perpendicular walls and the ceiling could achieve a 5dB(A) noise reduction.

Given the low frequency nature of the noise spectrum, 100mm thick fibreglass (32kg/m^3) insulation was recommended. To provide some protection against damage to the insulation when people were working in the room, a perforated sisalation (aluminium foil) facing was recommended. This could be provided as two layers of 50mm thick insulation for ease of handling, one with the perforated sisalation facing.

The final installation used 100mm thick fibreglass (32kg/m^3) insulation, without foil facing, due to delivery time constraints.

RESULTS OF TREATMENTS

Attenuation of Noise by Reduction of Signal Strength

The results of testing under several signal strengths are presented in Table 1.

Table 1. Noise levels with varying signal strength

Signal (Volts)	Noise Level Leq dB(A)	Noise Level Leq dB(A) at 315Hz
360V	86.1	-
360V	83.5	73.9
300V	83.3	73.1
250V	79.1	71.3

Notes:
1. The noise levels at 360V were measured on two occasions and the results are presented in Table 1.
2. L10 levels were 3-4dB(A) higher than the Leq levels presented.

From a review of Table 1 the data indicates that there was a significant reduction in noise level between 360V and 250V of 4-7dB(A). However discussions with the client's staff on site indicated that the LCFI cell would typically need to operate at 360V to ensure a reliable signal was received. Hence other treatments were required for the FIR.

Attenuation of Vibration and Noise Control Treatments

Noise levels with and without the treatments are presented in Tables 2 and 3. From the levels measured inside the FIR it was found that that the noise spectrum was quite broad, despite the injection frequency being at 283Hz. Hence overall dB(A) noise levels have been used to characterise the noise levels and noise reductions.

Table 2. Noise levels with treatments

Measurement Location	Noise Level Pre–Treatment Leq dB(A)	Noise Level Post–Treatment Leq dB(A)	Attenuation Achieved dB(A)
Inside the Office	65	46	19
Inside the FIR	94	84	10
Outside the FIR with Doors Open	87	78	9
Landing outside Wall Vent[1]	66	53	13
Below Slab[1]	61	51	10

Notes: 1. These levels were taken outside the building and were subject to road traffic noise.

From a review of Table 2 the data indicates that the reduction in noise levels ranged from 9 to 19dB(A). The office experienced the largest reduction of 19dB(A).

Table 3. Noise reduction from various treatments

Measurement Location	Attenuation from dB(A)		
	Vibration Isolation	Fibreglass Insulation	Overall
Inside the Office	14	5	19
Outside the FIR with Doors Open	3	6	9
Below Slab[1]	6	4	10

Notes: 1. These levels were taken outside the building and were subject to road traffic noise.

From a review of Table 3 the data indicates that of the 19dB(A) noise reduction achieved in the office, the vibration isolators provided 14dB(A) noise reduction. This confirms the calculated noise level findings that the noise was primarily structure-borne. The levels below the slab were again controlled by structure-borne noise. Levels outside the FIR showed a greater reduction with the acoustic insulation treatment, as the noise at this location was primarily air-borne sound radiating from the FIR via the open doors.

Figure 9 shows the office noise level spectrum in one third octave bands with the vibration and insulation treatments installed. Some irregularities in the data were observed (eg. higher levels after some treatments than prior to treatment at selected frequencies). This was caused by room modes in the receiving space, differences in measurement locations, and also some variation in background noise levels in the office. However the significant energy in the mid frequencies provides a clear representation of the before and after effectiveness of the treatments. The peaks in spectrum at 315Hz, 500Hz and 630Hz correlate well with the signal frequency and harmonics (283Hz and 566Hz).

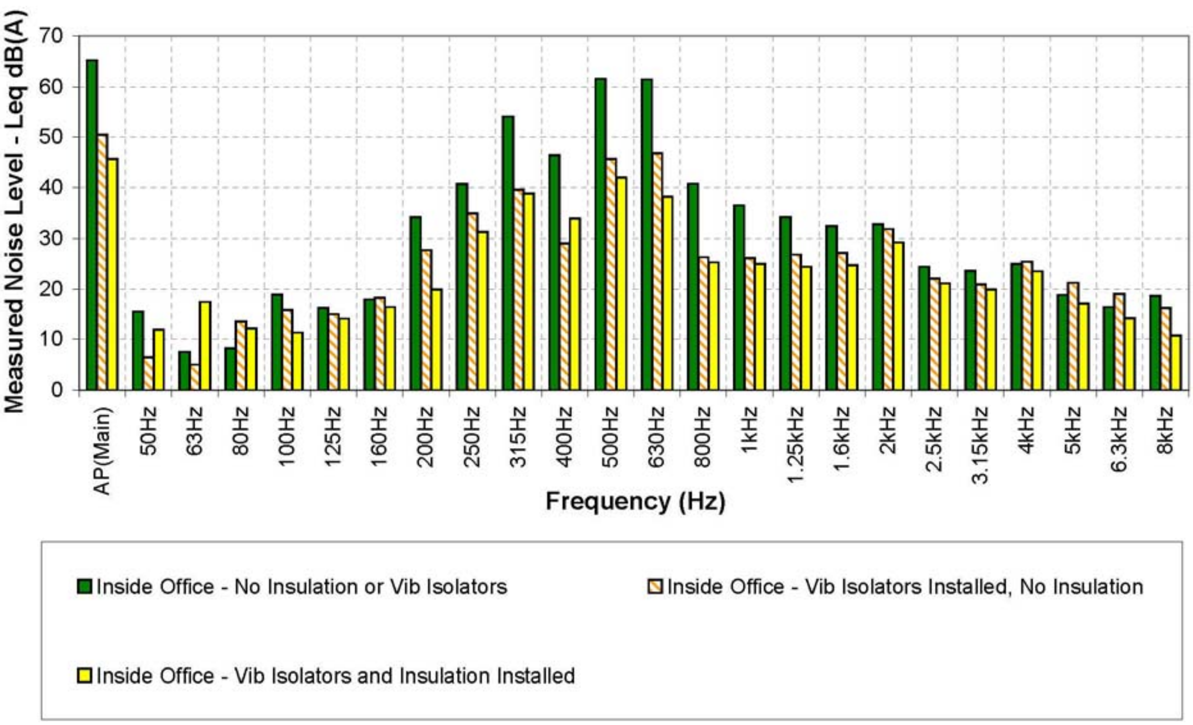

Figure 9. LCFI cell noise levels in office

CONCLUSIONS

Based on the measurements on site the following conclusions were drawn:

- Reducing signal strength from standard 360V to 250V achieved a significant reduction of 4-7dB(A), however this is not a viable option as the signal reliability may suffer;
- Noise levels in the adjacent office were reduced from 65dB(A) to 46dB(A), with vibration isolation and acoustic insulation treatments;
- Noise levels inside the FIR were reduced from 94dB(A) to 84dB(A) with vibration isolation and acoustic insulation treatments;
- The vibration isolation produced a reduction of 14dB(A) and the acoustic insulation produced a further 5dB(A) reduction in noise levels in the office, confirming that the noise was primarily structure-borne; and
- It is recommended that FIU equipment be mounted on vibration isolators for future noise sensitive installations, and insulation also be considered.

ACKNOWLEDGEMENTS

The author would like to thank the client's staff for their invaluable assistance during the project work and preparation of this paper.