A new compact isolated power supply for electrical Metrology at low signal levels

John Pickering, Metron Designs Ltd, Norwich UK,
Richard Thompson and Jonathan Williams, NPL, Teddington, UK

Abstract

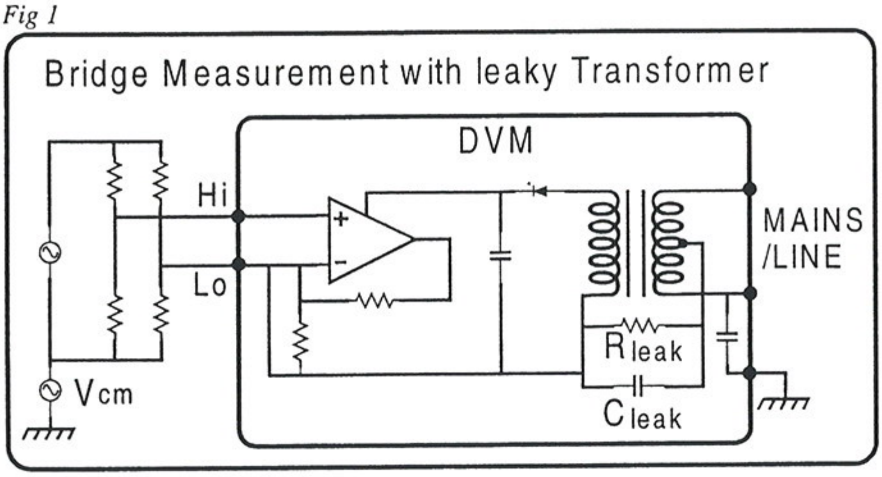
Many measurement situations call for true galvanic isolation between the measurer and the measurand (source). There are two basic reasons for isolation. For better measurements it is necessary to ensure that leakage currents that flow to power supply ground do not mix with signal currents and from the safety point of view that such leakage currents do not cause damage or injury. In these situations both DC and AC leakage can cause problems and whilst DC is relatively easy to control, AC leakage inevitably passes through the stray coupling capacitances in the Power Supply, particularly its transformer. In order to minimise this AC current 50/60 Hz linear supplies are the virtually exclusive choice of power supply technology in metrology applications.

This paper reports on the requirements, design and performance of a low power (7 W output) DC-DC converter capable of achieving leakage currents at its AC switching frequency of a few nanoAmps or less. It has the advantages of small size, lower capacitance and much higher efficiency than its counterpart. Early 2 W versions are used in a precision current source for the Large Hadron Collider project at CERN and in a new Wavetek Voltage reference source [1] and more recently it is being developed at somewhat higher power levels for general metrology applications at NPL.

The Importance of Isolation

The importance of power supply isolation has been covered extensively elsewhere but notably in NPL report DES 129 [2]. A common example of problems can be seen with the use of a mains powered digital voltmeter (DVM) as in Figure 1 where the presence of transformer leakage components clearly affects the voltage being measured in the bridge circuit.

Fig 1



The Hi terminal of the DVM feeds a very high impedance internal amplifier and negligible current flows through it. However, the Lo terminal is typically connected to the instrument's power supply and mains (line) transformer and on through the leakage components of that transformer, R_{leak} and C_{leak}, together with any other leakage paths to mains earth. The magnitude of the error is determined by the source impedance of the bridge, divided by the effective leakage impedance and this ratio constitutes the true common mode rejection ratio (CMRR) of the DVM, usually stated for a 1kΩ source impedance. The error current can be both AC and DC and will effect the measurement accordingly. It is also clear from Figure 1 that AC current from the mains, electrostatically coupled in the transformer can also flow back through the bridge causing additional errors.

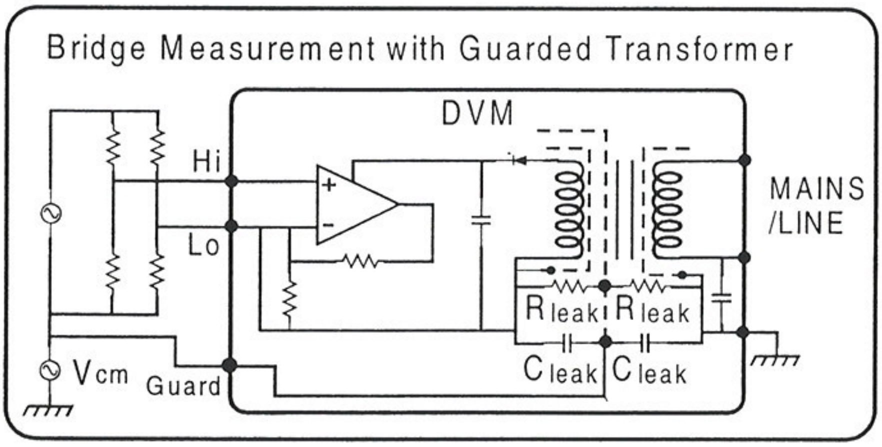
Techniques used to limit problems

There are several ways of overcoming the problems but all have their own characteristic shortcomings.

1. Actively Balance High and Low impedances. This can be done well with an active "Instrumentation Amplifier". However, the CMR (common mode rejection) of such circuits is limited by component matching and it may be impossible to handle the required voltage swing or to meet safety requirements.

2. Use Guarding techniques. Guarding techniques are well known to metrologists and essentially attempt to sink some of the leakage currents to a low impedance point at an appropriate, non interfering, potential. Sometimes circuit topology makes this impossible. The most effective place for guarding (and shielding) is in the transformer(s) using conductive electrostatic screens. Figure 2 shows the schematic of the DVM with an "ideal" screened and guarded transformer. Each winding is fully enclosed in its own screen and a guard screen is placed between the other two screens. The guard is connected to the source of common mode potential at the signal source and interrupts any leakage paths in the DVM's mains transformer forcing leakage current to flow through the guard back to earth rather than through the signal low as before. In effect it is an attempt to contain both source and measurer within a Faraday cage formed by the guard.

Fig 2



However, it is difficult to make the Guard interrupt 100% of the leakage paths. It is also often not possible to find an ideal connection point for the guard and measurements without a guard are made worse by the increased transformer capacitance and leakage to the Guard screen.

3. Battery Power! Perhaps the ideal situation is to have both measurer and measurand battery powered and this is practical for sub 50 mW consumption. However, this is not always perfect, particularly where high frequencies are concerned since they could be coupling asymmetrically to the outside universal "ground". It is also impossible to have continuous operation.

4. Make leakage components negligible. Lowering frequency in a given capacitance reduces AC current flow which is why (until now) 50/60 Hz transformers dominate measuring applications. However, the 50/60 Hz transformer tends to be large and inefficient, especially when screened sufficiently well for measurement applications. The large size leads to lower leakage resistance and high capacitance for a given insulation thickness so it would appear that small transformers could offer <u>better</u> leakage performance. Switching supplies are also much more efficient in the range of power (1 W to 30 W) most common in instrumentation, thus running cooler and reducing thermal errors.

High Frequency AC Leakage Currents in Switching Supplies

In order to benefit from switching it is necessary to operate at frequencies high compared with 50 Hz, together with still higher harmonics. These high frequency components then couple more readily through capacitance in the transformers. The leakage current can be measured using an oscilloscope or ammeter as shown in Figure 3. An example of the results obtained can be seen in figures 4 and 5 which show the measured leakage current across the isolation barrier of two so-called "medical" supplies.

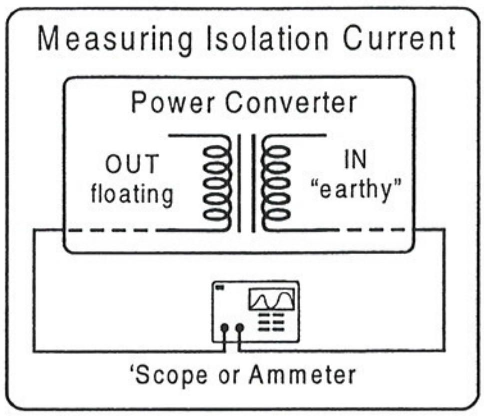


fig 3

Fig 4 NFS40-7910

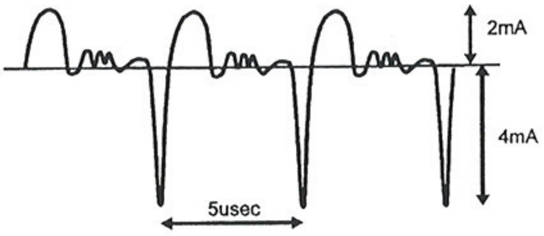
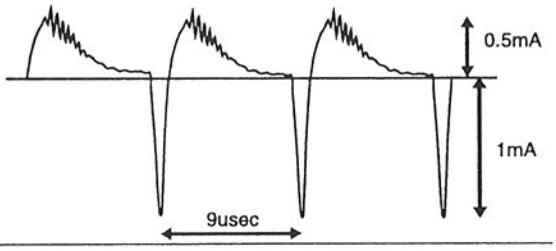


Fig 5 MS45



Other commercial isolated DC-DC converters give similar results with seldom less than 1 mA of AC current through the isolation barrier at the switching frequency.

A very high Isolation, Low Leakage DC-DC Converter

A 7 W DC-DC converter has been developed by Metron Designs Ltd under contract to NPL who have specified and tested it. The design utilises the techniques listed below.

1. The transformer winding potentials move in an electrostatically balanced way by using push-pull rather than single ended drivers.

2. A Linear Technology LT1533 [1] 1 A switching regulator has been adapted by the addition of "H-bridge" drive mosfets to reduce the peak input voltage swing from a 12 V input power supply. This component utilises slew controlled Voltage and Current drive waveforms in a PWM configuration. The H-Bridge primary drive halves the peak to peak voltage swing on the primary for a given input Voltage and utilises all the primary copper all of the time whereas single ended drives or pull-pull drives as described in the LT1533 data sheet result in 2X over-voltage on the "Off" swing.

3. A special transformer with full, near perfect, Faraday cage screening around each of the primary and secondary windings has been developed. This is covered by patent application. [4]

4. The resulting primary and secondary windings are separated by several millimetres and magnetically coupled by an enclosing "shorted turn" winding that does not carry significant induced voltage.

5. The frequency is kept reasonably low (7 kHz) by the use of modern "amorphous metal" materials giving very high permeability together with low losses up to 100 kHz.

Fig 6

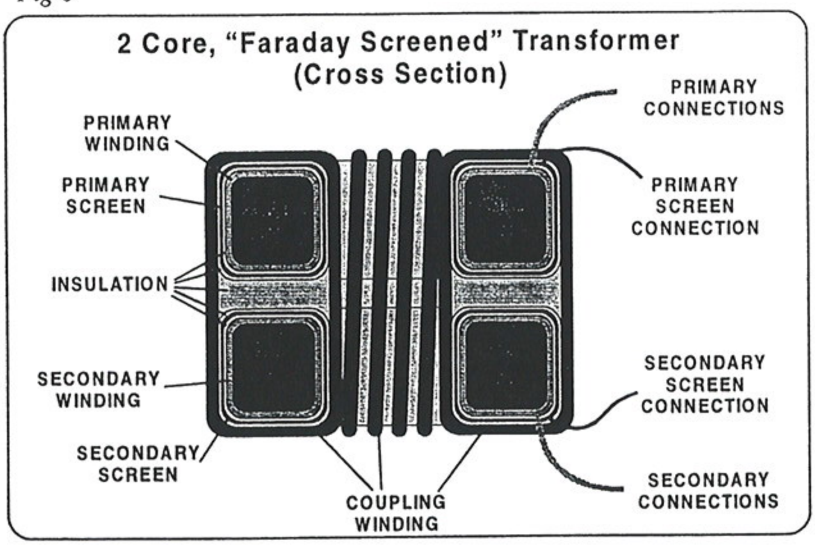


Figure 6 is a diagram of the transformer which uses resistive "Faraday Cage" screens to enclose fully each winding (and core). By using injection moulded, carbon fibre loaded plastic screens at a resistivity of around 5 Ω per square, the screens are near perfect electrostatically yet of sufficiently high resistance to load the transformer negligibly. At 3 turns per volt even a 1Ω single turn shunt action from the screen dissipates less than 100 mW.

The two enclosed wound cores are magnetically coupled with a number of turns of wire connected as a closed loop. This coupling winding then encloses both cores forcing the magnetic field in one core to be equal (and opposite) to the other. The coupling winding therefore has no net voltage induced in it.

Results

The isolation performance of the supply has been tested using an oscilloscope as shown in Figure 3. The oscilloscope was fitted with a x10 probe with an input impedance of 10 MΩ with about 10 pF in parallel. An example of a typical oscilloscope trace (scaled to allow for the x10 probe) is reproduced in Figure 7. It can be seen that the signal has a period of about 170 µs corresponding to the drive oscillator frequency of 6 kHz. The peak-to-peak amplitude is approximately 500 µV and this corresponds to a current of 200 pA p-p taking the impedance of the probe to be 2.7 MΩ at 6 kHz.

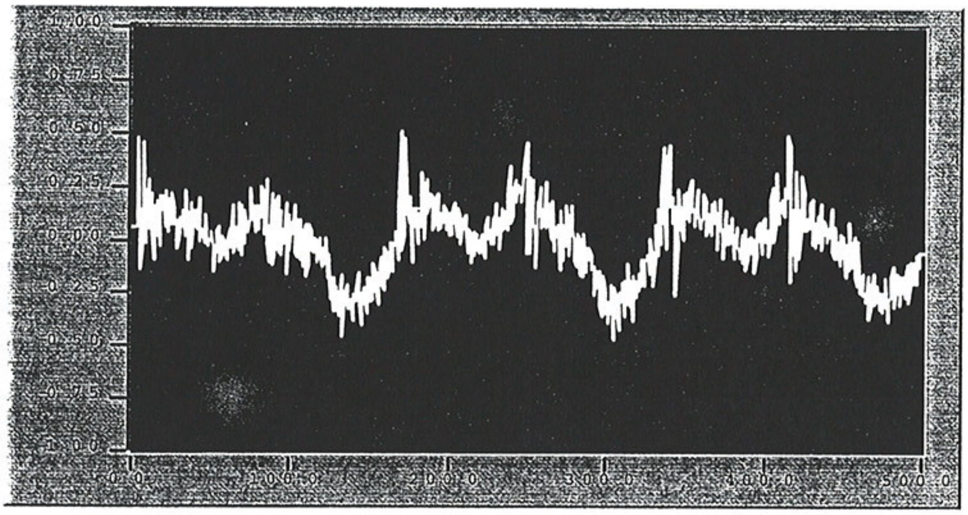


fig 7 Y-axis in mV and X-axis in µs

Applications

The device is being developed in the first instance to power existing Zener-based voltage standards at NPL. This will allow them to be measured against the Josephson system whilst powered from the mains, eliminating the possible problem of a change in value between mains and battery operation. It is hoped that the supplies will also be used more widely at NPL as a compact alternative, with battery back up, to the bulky 50 Hz isolated power supply used at present in low noise measurement systems. The small size and weight of the supplies will mean that they can be incorporated into the instrument case without making it large and heavy.

Conclusions

For many precision measurements it is necessary to isolate the measurer from the measurand and to ensure that no AC currents can pass through any remaining coupling capacitance. For externally powered instruments or circuits, very special high isolation power supplies are needed which, in turn, require special transformers and driving techniques. A solution, based on a patented transformer and sophisticated slew controlled H-Bridge drive circuits, has been designed and offers isolation leakage current performance at least 300 times better normal "measurement" mains/line powered supplies at the same power level and some 10^6 times better than typical DC-DC converters.

References:

1. Wavetek 7000 series data sheet
2. NPL Report DES 129, B P Kibble, I A Robinson
3. Linear Technology LT1533 data sheet
4. UK Patent Application: 9524566.8
   International Patent Application: PCT/GB96/02976