Setting new standards for DC Voltage Maintenance Systems

A Solid State DC Reference System

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Many organisations rely on 10V DC standards as their primary DC reference. However, the routine maintenance of such devices is not only labour intensive, but requires a high degree of metrological skill to perform the measurements and analyse the accumulated historical data. This paper describes an innovative new lightweight voltage standard and integrated voltage maintenance system that fully automates the voltage measurement process from import of traceability through to certification.

INTRODUCTION

Whilst Josephson 10V arrays are pushing into uncertainties of parts in 10^9 or even 10^{10}, they continue to need costly and bulky cryogenics. Presently available metrology class zener references need permanent battery back-up support and fairly expensive 7V to 10V step-up and trim arrangements. Zener reference systems require connection to external special purpose scanners with external wiring arrangements, giving considerable inconvenience and possible inconsistency of set-up. Furthermore, battery-backed ovens around the zener are required to avoid hysterisis voltage steps common to all zeners and, as will be shown, the consequences of providing this support severely limit available performance, substantially increase costs and decrease reliability. The design work described in this paper exploits a new patented technique to "reset" any hysterisis step through a conditioning process. This in turn allows a re-think of the basic design of reference modules giving much improved stability and reliability with sufficient cost, size and power reduction to make viable a new compact system approach to DC volt maintenance.

HYSTERISIS AND CONDITIONING

Hysterisis:

Hysterisis steps in zener voltage references are a well known phenomenon and are permanent or semi-permanent jumps in voltage caused by temporary exposure to temperature differing from the normal operating temperature. These excursions from normal may be due to loss of power or exposure to adverse ambient conditions. The magnitude can be as high as 10ppm for temperature excursions down to 0°C and, in the case of ovened references at a typical 60 - 80°C, 2ppm is commonplace for power failure alone.

Hysterisis Recovery:
The recovery from a hysterisis step is not well described in the literature. There is a general assumption that recovery to the original value does occur but our own tests for one type of modern popular zener reference indicate that the recovery time-constant is <u>at least</u> 6 months and in some cases recovery <u>may not occur at all</u>. In summary, the voltage of the zener is dependant on its history!

Oven Support:
The usual method for overcoming this problem is essentially to ignore it by disallowing changes in environment through provision of permanent oven support to maintain the zener at constant temperature. This sounds simple but there are major problems involved. The oven must be held at a high enough temperature to maintain control at the highest ambient likely to be encountered. To this must be added any self heating effects outside the oven s control range together with sufficient control margin and this ultimately leads to a junction operating temperature of around 60°C - 80°C. The downside consequences are high power consumption of 5W-30W per cell, needing lead acid batteries & resulting in poor reliability (of batteries), high weight, high temperature gradients degrading TC s and accuracy at the terminals, high cost, significant Power-on/Power-off differences and high voltage/time gradient. And these problems in turn limit the potential system application of these devices.

Conditioning:
Many of the characteristics of the observed hysterisis in zener references can be likened to mechanical "stiction" problems and the very label "hysterisis" gives a clue to a possible recovery process. We have shown that, at least to a first degree, the effects of hysterisis can be reset by a process akin to de-Gausing a magnet. The chart (fig 1) shows results of tests on a variety of reference zeners. These tests along with other data, which has been omitted for brevity, indicate hysterisis steps are bistable for a given temperature step, they increase with magnitude of step, recovery is very slow or non-existent, conditioning recovers at least 90% of the step.

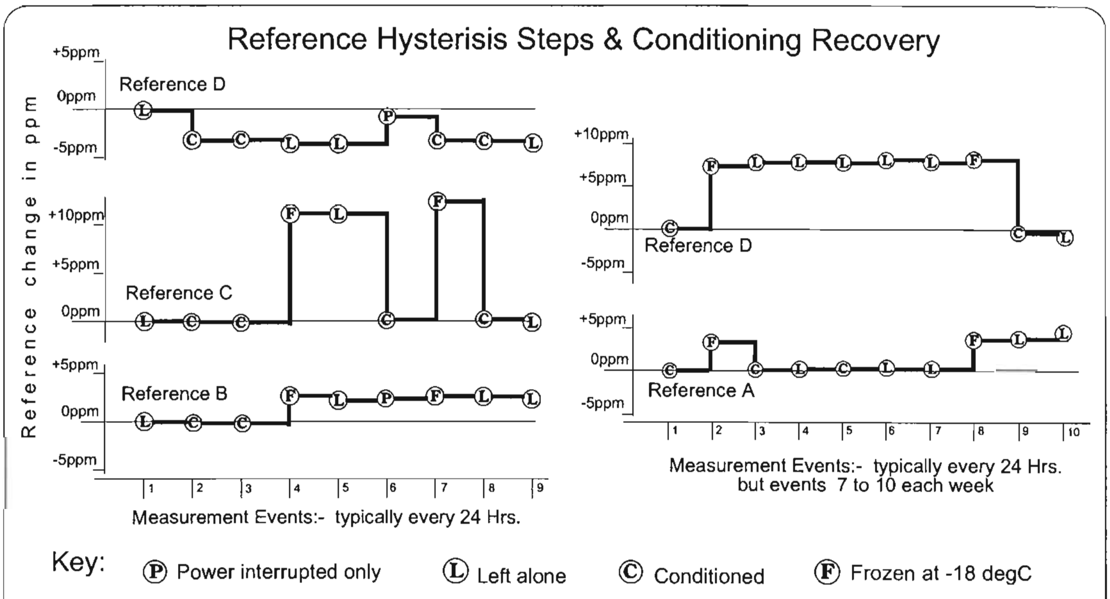


Fig. 1

The Conditioning Process:

The conditioning process has been patented (US No. 5,369,245) and as implemented in a proposed reference module takes advantage of the excellent LTZ1000 reference from Linear Technology Inc. This device incorporates a heating element on the zener chip together with transistors that can be used to accurately sense the chip temperature. See Fig. 2.

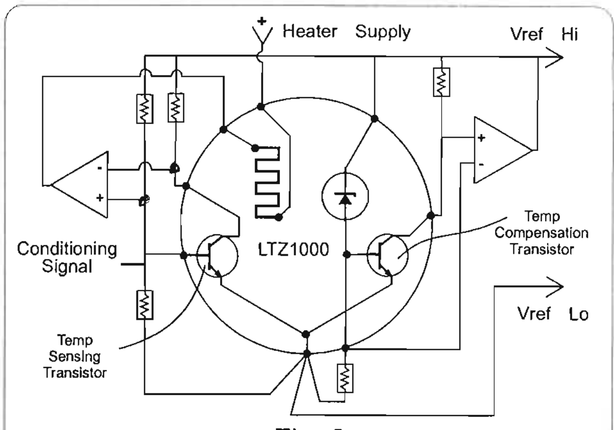


Fig. 2

The actual circuit uses the temperature compensation transistor to both compensate for the zener and to sense the chip temperature as part of the control loop. This leaves the sensing transistor free to be used as an independent temperature monitor.

The normal application of this device utilises its components to run at a very precisely controlled and maintained temperature (to < 1 millidegree). Briefly, the conditioning process deviates the chip temperature about the norm with a gradually reducing magnitude over a period of about 4 hours. This is done following a power interrupt (or on user demand) and prior to normal operation. See Fig. 3

It is important to realise that for best repeatability this is a very accurately controlled process - the chip temperature target value is accurately deviated and the loop responds normally, resulting in each complete cycle being accurately repeatable. In effect this erases previous histories for the zener and establishes the same one each time it is repeated. In the reference module design a small NiMH battery is incorporated so that conditioning does not get triggered unnecessarily by short term interrupts.

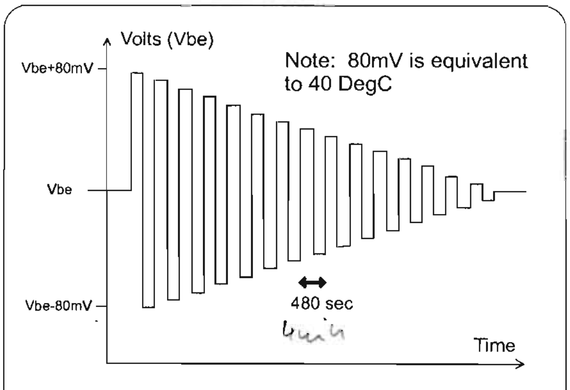


Fig. 3

Advantages of Conditioning:

The absence of essential and relatively unreliable Lead Acid cells is an obvious advantage but the consequential benefits are of much greater importance. In particular, because we no longer fear extremes of temperature excursions, we can operate the zener at around 45°C with the following benefits:

1. Stability:

Our own work and that of others, notably Peter Spreadbury of Cambridge University in the UK, indicate that long term drift is halved for every 10°C drop in chip operating temperature. The data below is derived from two small groups of references operated identically in the same measurement system but with one group at around 80°C and the other at 45°C.

Operating Temp.	80°C	45°C
Group Annual Mean Drift	-1.2ppm	-.06ppm
Standard Deviation	.8ppm	.25ppm

The 2σ uncertainty in the base measurements is about .2ppm per annum.

2. Power consumption:
A complete reference module based on this technology and including 7V to 10V step-up and trim, 1V/1.018V output, battery charger, scanner and indicators consumes less than 1W from the line input and has an internal ambient rise of less than 2°C.

3. Temperature Coefficient:
The low self heating helps maintain low temperature coefficient without the need to provide ovening of any components other than the zener.

4. Internal scanning:
The very low temperature gradient makes possible the incorporation of scanning switches within the reference module for easy and accurate external bussing in a mainframe.

5. High Reliability:
If a reference NEEDS battery support then it cannot be relied upon if the battery fails. Its reliability is therefore dependent on its batteries and the effects of handling, environment and transport on their state. They are notoriously unreliable. The "conditioned" module does not need batteries and those that it incorporates for user convenience are of a technology that is much more reliable.

DESIGN OF A REFERENCE MODULE

To design a reference module taking advantage of the conditioning capability and meeting the requirements for use in an automated reference system, certain key design requirements must be met:

Low Power Consumption - leading to very low self heating:
The whole reference module, including 10V output, is designed to operate from 12V internally. The zener and on-chip heater consume about 25mA and the whole of the remaining circuitry about 10mA. To this is added the trickle charge rate of the internal batteries of about 10mA. Allowing for line voltage range and by utilising an inductively smoothed supply for ultra low noise and efficiency, the net power consumed is about 1 Watt. The following conditions are then met:

Internal temperature rise with full power and charging:	**1.5°C**
Internal temperature rise with line off, battery support:	**1°C**
Line/Battery difference	**0.5°C**

The actual zener chip temperature is held to << 1 millidegree under all these conditions.
Low Offset (<<100nV) Scanning:
It was decided to incorporate the scanning switched inside the reference module to minimise signal wiring - see Fig. 4.

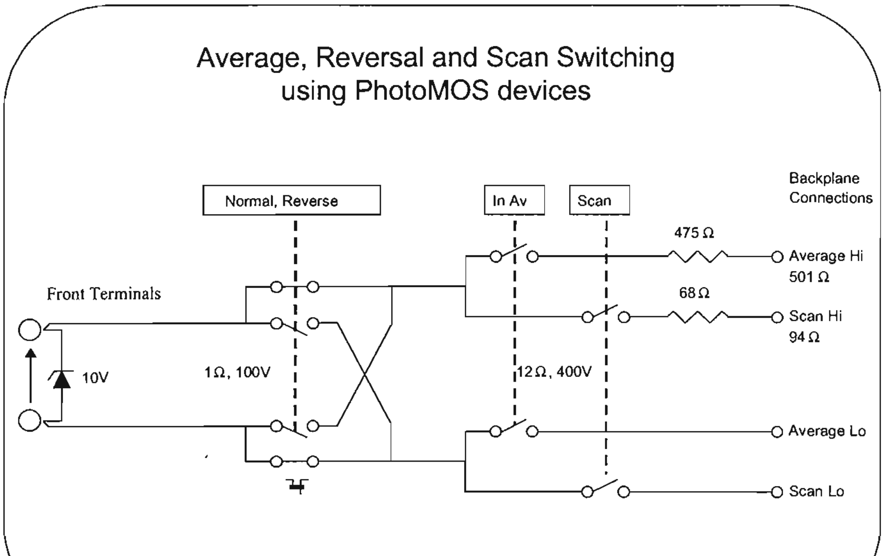


Fig. 4

There are two switched outputs, one controlled by an external selection line allowing one particular reference module s output to be selected for applying to an output bus. The other (not shown in Fig. 4) is under control of a front panel switch and enables output to be placed on another bus used for electrical averaging of many modules. In each case performance to << 100nV is achieved by using differential solid state switching. The switches chosen are quite remarkable, providing 400V of OFF isolation and a few tens of Ohms of ON resistance. Under normal conditions the OFF leakage is no more than a few picoamps. These optically controlled devices consume 3mW to turn ON and with reasonable care can achieve less than a few tens of nanovolts

Very accurate 7V/10V Step-up:

The 7V/10V step up is one of the most critical aspects of the design. It has to be adjustable over about ±2% to allow for different zener voltages and this must be accomplished without degradation of stability. For some years now we have been successfully using of arrays of identical resistors in precision standards applications. This gives statistical averaging of random variations between devices and with careful design common forms of systematic error can be made negligible. Consider the step-up arrangement in Fig. 6 which includes extra elements for coarse gain setting.

Here any one resistor s contribution to errors can be shown to be about 1/20th of its deviation from the others. For certain types of resistance networks with symmetrical packaging, a standard deviation of TC matching between elements of <0.05ppm/°C is realisable if package position related systematic errors are ignored. This is justifiable in a typical ratiometric design because placing of particular elements in particular arms of the divider can usually balance these systematic errors out. For the circuit in Fig. 6 with typically 12 elements of similar contribution of error:

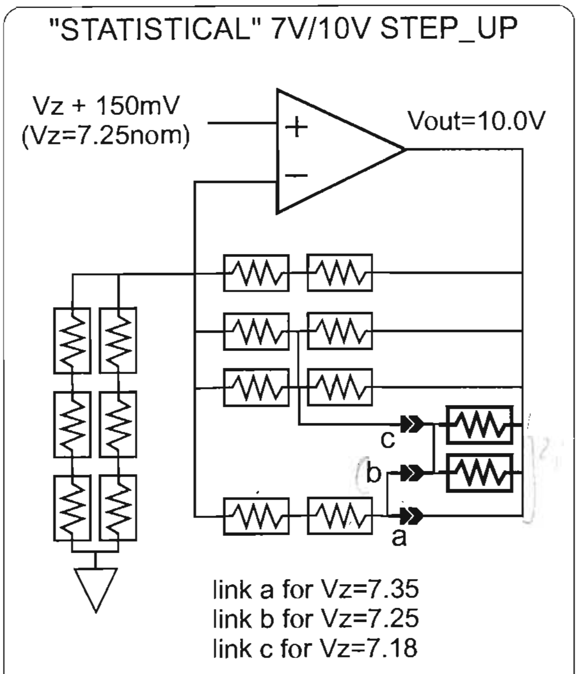


Fig. 6

Standard deviation of single contribution:
= 1/20 x 0.05ppm/°C = **0.0025ppm/°C**

For 12 equally contributing elements the standard deviation of output is then:
√12 x 0.0025ppm/°C = **0.009ppm/°C,** giving a 2σ probability of 7V/10V step-up TC
< .02ppm/°C

Similar calculations and resistor network evaluation give 7V/10V step-up long term stability performance (2σ) as: **<0.2ppm/year.**

Since these variations are random and even any resistor package systematic errors are random in polarity, we get further advantage when modules are averaged suggesting that a ten cell bank ought to achieve a worst case, including both zener and step-up errors, of 0.3ppm per year absolute at the 10V level.

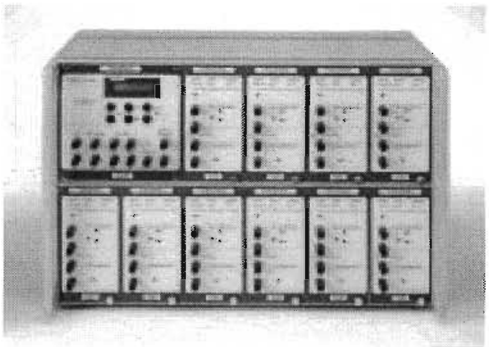
High Isolation Power Supply:
One downside of not needing battery support is that operation under line power must be indistinguishable from true battery isolation. For this reason a special line transformer was developed which operates at 50% lower flux density than is conventional and has only about 1pF of primary to secondary capacitance with 4kV of secondary isolation. The net result is that power may be switched ON and OFF whilst a null detector is connected to the 10V output with less than 1μV of "glitching" observable as the power is switched. The reference may be directly compared with a Josephson array while under line power without causing array step instability.

Status Communication:
For use in a system it is important that the system controller and its data processing cannot lose track of reference module status. A status register is loaded within the module with various status bits such as Power Supply Condition, In or Out of Average, Oven OK and, most importantly, a unique serial number 18 bits long set at time of manufacture. When a particular reference module is selected this data can be read out by a simple low speed clocking mechanism.

TRANSPORTABLE REFERENCE

Four reference modules are incorporated in a rack enclosure known as a 'Transref' which also provides the facility to electrically average the 10V outputs. This unit is supplied with a rugged transit case and recording temperature monitor as a fully transportable reference for intercomparison purposes which does not need to be maintained under battery power during transport. It also has the ability to be directly interconnected to the laboratory reference system described below to automate the intercomparison process.

AUTOMATED LABORATORY REFERENCE SYSTEM



An automated laboratory reference system, known as the Nanoscan system, is provided by a rack enclosure incorporating the necessary signal and power interconnections for individual reference units and a null detector. The Nanoscan system can scan up to 21 independent channels. It controls the switching in the modules including the selection of Forward or Forward/Reverse measurements for elimination of thermal emfs. The Nanoscan module has a built in low noise null detector with a dynamic range of ±1mV and a resolution of 0.01µV allowing individual module outputs to be compared with the system hardware average. Interface with a PC running software to control the system is via a fibre optic link to ensure high isolation, and a status display and front panel controls also allow manual operation. The 10V hardware average (HAV) may be compared against a external 10V reference to import traceability or to calibrate a UUT 10V standard. An External Reference input is assigned to Channel 21 to allow connection of external references for automated measurement and importing or exporting traceability. Automatic measurement of multiple external references is available via 10V Scan Modules which may also be fitted into the rack - External references are not included in the Hardware Average for reasons of impedance matching. A 10V buffered output, for driving resistive loads such as voltage dividers, and a 1V output are also derived from the Hardware Average.

MEASUREMENT AND ANALYSIS SOFTWARE

The PC based acquisition software, written in Labwindows CVI, controls the scan and measurement events. Microsoft Excel is then used for data analysis with a number of purpose designed 'Add-ins' available. From within Excel pull down menus provide access to a number of tools for performing common tasks such as analysing drift rates, assigning HAV values , graphing and reporting of measurements, and generating calibration certificates.

CONCLUSIONS

The knock-on effects of designing for low power consumption and high isolation line power are tremendous. A reference module has been designed for system use to give a self contained volt maintenance system and also providing a transportable reference not requiring power from heavy unreliable batteries during transport. The software and analysis tools provide an efficient solution to the problem of maintaining a high integrity laboratory reference with the minimum of manual intervention, allowing meteorologists to concentrate on tasks most suited to their skills