An Intelligent Voltage Standard

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Abstract—**Voltage standards based on solid-state references are now commercially available with drifts of the order of a few parts per million per year. In order to achieve a good measure of confidence when dealing with these stabilities, it is usual to operate a large group of standards which may be readily intercompared. Thus any anomaly in one member of the group can be detected, and appropriate action taken.**

The Intelligent Voltage Standard (IVS) performs the task of intercomparing a group of eight Zener diodes under computer control. It uses ordinary commercial components and the controller is a slightly modified simple microcomputer. It presents information to the user about any anomoly in the group of Zeners that has been detected and recommendations for action. The computer program has data on the Zener "aging" rates and so presents the user with an expected value for the output of the standard on any day that it is used.

I. Introduction

The Intelligent Voltage Standard (IVS) is a machine which operates as a simple, self-contained, self-checking group of voltage standards which can operate largely independently of its users.

The objective of the IVS design, which was a three-year Ph.D. project, was to use a small group of between 6 and 16 compensated Zener diodes, commercially available for a few dollars each, with a scaling amplifier to produce a 10-V standard in whose output a user will have very high confidence. The work of maintaining charts showing aging rates, etc., should be handled by the controlling computer and a current value for the output voltage, correct to within one part per million, should be presented to the user. The temperature of the environment may be from 15 to 25°C.

The confidence in any measurement can be improved by using a number of standards and averaging the results so obtained. This assumes that all the standards are working well. The IVS technique allows for one or more of the standards not to be performing as usual, and for this to be detected by intercomparing them. The user is told of any anomolies arising and, with appropriate action, the standard will have better short-term stability than one that does not use this technique.

It is necessary to convert the tasks, records, and intuition of the skilled standards laboratory operator to a set of procedures and an appropriate data structure which will be used by the computer. It is also necessary to provide the computer with the appropriate interface hardware which will enable it to carry out measurements and adjust certain physical parameters of the standard.

In addition to the hardware, there exists a set of procedures which are used in the operation of the standard, and a collection of data which are used, and possibly modified, by those procedures. In operating a conventional standard cell group, the scope of the procedures and the amount of data in a history file are considerable, ranging from absolute quantities and well-defined techniques to subjective opinions and judgements. While the former are readily implemented in an automatic machine, the latter present difficulties which at present are still best met by the expert human operator.

II. Operation of the Standard

To routinely measure and keep track of the relative voltage differences between the Zener references, a microvoltmeter is connected between the outputs of a pair of reference devices which share a common ground connection. The voltage difference is taken as the average of several readings on the microvoltmeter, which need not be a high-resolution instrument if the references are well matched. For a group of N reference devices it is necessary to make a minimum of $N - 1$ measurements of voltage difference.

The previous calibrations of the standard will have resulted in an accumulation of data about each of the reference devices including the voltage at various times, its rate of change, and the overall behavior of that device. These data are now used to compute a voltage for "today" for each device, and by subtracting pairs of these, an "expected" set of voltage differences. The measured data are now compared to the expected data and a decision is made regarding the "goodness" of each member of the group.

The next procedure which is automatic in operation is a calculation of the output of the standard if only the "good" devices are used: the average of their present expected voltages is scaled by the gain of the output stage. The standard is only reconfigured to give this value if the operator agrees.

The collection of data which represents everything that is known about all the members of the reference group is called the "data pool"; it should ideally contain the opinion of the operator who has supervised the instrument, as this will be stored in his memory and may influence his agreeing to any reconfiguration of the standard. However,

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this is difficult to implement and has been avoided. The data pool contains two classes of information, short term and long term. Long-term data have been verified by calibrations, and so may be assumed to be correct and unchanging and part of history. Short-term data have been collected since the last calibration, and are not necessarily correct, but are qualified by an expected error limit, defined by the long-term data. At calibration, a procedure which only takes minutes under computer control, the short-term data are verified and then reclassified as long-term data.

III. Overview of the IVS

The operation of the IVS is controlled by a Basic program which runs in a modified Commodore 3016 microcomputer. The user communicates with the IVS through the keyboard and display of the computer which are arranged to be as "user friendly" as possible.

The program continuously monitors the behavior of the reference diodes and, when requested, provides interactive control of the standard. The interactive part of the program is operated by a set of commands which provides services for inspection of performance, calibration, and the selection of devices to define the output of the standard. The user selects the desired command from a menu displayed on the computer screen.

The IVS hardware consists of a single height Eurocard rack (6 in high by 19 in wide by 10 in deep) which contains the control and measurement circuitry, and a separate unit of similar size which houses two Zener-diode modules and their associated circuitry. Each Zener-diode module contains eight references which are housed in an isothermal enclosure running at 35°C. A block diagram of the IVS is shown in Fig. 1. Its main parts are as follows.

1. References: These are 7.5-mA compensated Zener diodes type 1N827. Each diode was tested to find out its optimum operating current for near-zero temperature coefficient. Noisy devices or those showing unusual behavior were rejected at this point.

2. Analog Switches in Signal Selector: These are LOCMOS devices type number HEF4051 and HEF4066 by Signetics Ltd. Each device was checked for satisfactory values of leakage current, offset voltage, and ON resistance.

3. Microvoltmeter (Preamplifier and A/D Converter): The A/D converter requires a preamplifier made from a chopper-stabilized amplifier type ICL7650CPD which drives a converter of conventional 8-bit type whose output is opto-isolated from the control circuitry. The preamplifier was tested for input bias current, offset voltage, and noise.

4. Output Stage: This is a two op-amp design comprising an ICL7650CPD chopper amplifier front end driving a NE531 output stage. The precision feedback divider was a quaternary alloy wirewound device supplied by H. Tinsley & Co. The chopper amplifier was checked for input bias current, offset voltage, and noise. The feedback

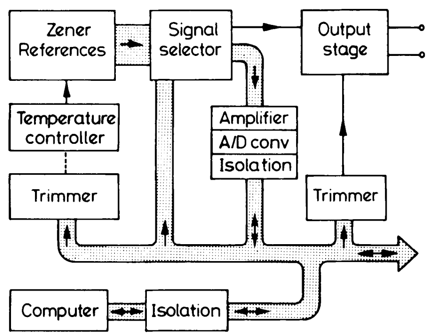

Fig. 1. Block diagram of the IVS.

resistor was tested for temperature coefficient: it was found to be +0.3 ppm/°C, so high confidence in the 10-V output of the standard is not achieved on days when the room temperature is outside the 17–23°C range.

5. Computer and Interface: A Commodore 3016 microcomputer acts as the controller of the IVS and provides the means of communication with the user via its keyboard, screen, and printer. It had added to it an extra 6522 VIA chip to act as a bidirectional port for IVS data and as an output port to control the IVS address bus, a 5-V regulator to power the isolation board, and 4 kbytes of CMOS RAM with battery backup to give nonvolatile data storage.

The computer program, written in Basic, has an automatic routine, at present performed once a day, to measure the relative voltages of the group of Zener diodes and then to make a judgement on the results of the measurement task. The judgement task is based on the idea that, in the short term, the voltage of any diode will follow a straight line when plotted against time. For each device, the program maintains a short history in the form of the previous five-days measurements so it can construct an "expected" value for the present measurement. The actual result is compared to this and, if there is a sufficiently large discrepancy, it will be reported. The program over the next few days collects further data to attempt to analyze the particular anomoly as a "step," a "spike," or a new Zener voltage rate of change against time.

Second, the computer program has an interactive routine which is continuously available to the user except for the 5 min when the automatic self-measurement is performed. On pressing any key the following menu of commands appears:

S show IVS status,
R run measurement sequence,
M display "goodness" map,
D display calibration data,
U update calibration data,
H select refs by hand,
P select printer output,
$ enter slope data,
G update output stage gain, and
W continue waiting.

There is space here to describe only one of these and to show one of the computer's displays, entitled the "good-

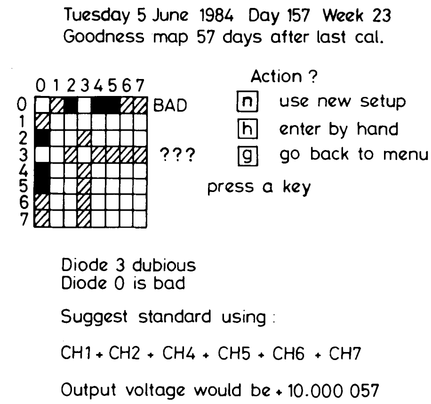

Fig. 2. Goodness map.

ness" map, (see Fig. 2). This presents the results of the latest measurement of the voltage differences between references in the group compared to the set of expected differences generated from the calibration data. The results of this comparison are displayed on a grid of eight-by-eight squares, one line for each reference, and each square is filled-in in one of three ways: if the error is less than 1 ppm, the square is left empty; if the error is more than 2 ppm, it is filled in solid; if it is in between, the square is filled by a hatched pattern.

Consider the top line of the grid in Fig.2 which has 0 on the left and BAD written on the right. This shows how well the difference between reference 0 and the other references in the group compare to the expected differences from past calibration data. Three of the squares on the top line of the grid are solidly shaded, indicating that three of the differences are more than 2 ppm from that expected, and three more are hatched to show an error of between 1 and 2 ppm. In all then, device 0 does not appear to be performing as expected.

The second line of the grid in Fig. 2 tells a very different story for device 1: in only one case is the difference with another device not as expected and that is in comparison to device 0 which is already under suspicion. So the assessment continues for the other devices.

The goodness map presents information visually to the user on how the references are performing. A normal system might average the output of the eight references so any one which is approaching 2 ppm of error from its expected value would be contributing 0.25-ppm error to the average. The computer algorithm uses this as the level at which the reference is better omitted. So the algorithm declares a reference "bad" if it is more than 1 ppm different from *all* the other devices (or more than 2 ppm different from four devices or any combination of these). A device is declared "dubious" if it is more than 1 ppm different from five other devices.

On the basis that the remaining references are performing well, their voltages are assumed to be close to those given in the long-term data pool, and the aging rate is assumed to be accurate too. So the output voltage of the standard can be predicted with confidence from the average of a set of references which are all within 1 ppm of their expected values. It is left to the operator to follow the computer's advice or to do otherwise if he wishes.

IV. Performance of the IVS

A group of eight 10-V standards are maintained at Cambridge and their values are traced to the National level about every six months by courtesy of the Division of Electrical Science of the National Physical Laboratory. The output of the IVS was compared to this group and it rose from 48 to 65 μV above 10 V over a period from September 1985 to January 1986, and from January to May 1986 it rose further by 8 μV or 0.8 ppm. In this latter period, the IVS was measured every two weeks from mid-February to mid-June; then, the readings for the IVS output in microvolts above 10 V were 70, 72, 76, 66, 70, 71, 80, 77, and 72. The mean value of these readings is 73 μV above 10 V, and the standard deviation is a 4 μV or 0.4 ppm. The noise on the output is about 1-μV peak to peak. It should be pointed out that the temperature of the room in which the IVS is used is not controlled in any way, and the lower output obtained in September 1985 was almost certainly due to this.

After operating the IVS for several months the goodness map is seen to be more shaded, and instead of six or more references still appearing to be close to their calibration data, if there are only four or so then it is time to recalibrate the IVS. With the in-built computer, this is an easy and speedy process. Just *any one reference* needs to be measured in a way that can be traced to the National Voltage level, and the value of this single reference is entered on the computer keyboard. The computer then automatically compares all the other references to the one whose value has been given and so new voltages are calculated for all the references. Also each new voltage is compared with that obtained at the last calibration to allow an aging rate for each reference to be calculated. Finally the references data are all listed on the computer screen and the operator is invited to use it or amend it by hand if he so wishes.

V. Developments of the IVS

It was mentioned that the IVS contains two Zener-diode modules each containing eight references. So far only one eight Zener group has been used to define the IVS output and the performance for that is quoted in this paper. The other module may be filled with any new Zener type appearing on the market and an assessment made in a qualitative way using the goodness map. Eventually, extra confidence will be expected from the IVS by having a second group of references. Also a development is planned to allow the scaling factor of the output stage to be determined with confidence by adding a mark-space voltage divider to cut the 10-V output down to 6 V and to compare this with each of the references in an extra line in the goodness map.

VI. Conclusion

The Intelligent Voltage Standard has been found to be easy to operate and successful in alerting the user to a number of anomolies that have occurred in the reference group. The stability of the standard compares excellently with the best of the other standards in the group at Cambridge and yet the IVS was built on a very limited research budget with cheap reference devices.

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