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The Transfer Voltage Standard for Calibration Outside of a Laboratory

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Abstract: The transfer voltage standard is designed for transferring the analog voltage from a calibrator to the process control workstation for multi-electrode electrolysis process in a plating plant. Transfer voltage standard is based on polypropylene capacitors and operational amplifiers with tera-ohm range input resistance needed for capacitor self-discharging effect cancellation. Dielectric absorption effect is described. An instrument for comparison of reference and control voltages is devised, based on precise window comparator. Detailed description of the main task is given, including constraints, theoretical and practical solutions. Procedure for usage of the standard outside of a laboratory conditions is explained. Comparison of expected and realized standard characteristics is given.

Keywords: Voltage standard, Calibration, Polypropylene capacitor, Dielectric absorption, Window comparator, Metrology, Electrolysis, Plating.

1 Introduction

Calibration in laboratory environment is a highly repeatable process, where all relevant quantities are controlled or at least well known. Calibration outside a laboratory introduces many new parameters that can affect the results and the metrological system as a whole.

Specific requests and problems always arise when measurements are performed in the field. Non-standard solutions are needed when many constraints are present, such as low cost, temperature variations, short period given for the project to be finished, obsolete and non-standard technology, etc.

One of the greatest challenges of calibration in the field is to ensure that transfer voltage standards (TVS) maintain their metrological specifications when used outside of a laboratory. Variations in temperature, humidity and pressure, mechanical stress, EM interference, fluctuations in power voltage – these are some of the error sources affecting the voltage standards, [1, 2]. Adding the requests for the high accuracy (0.01%) and the cost efficiency factor, the transfer voltage standards becomes a technology challenge. Having

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this in mind, low-cost, standard voltage standard devices used in a laboratory all have certain shortcomings:

Dry cell/battery with a voltage divider – batteries have clean DC voltage without EM interference, but its stability is susceptible to voltage fluctuations due to the chemical reactions inside a cell. The finite resistance of the voltage divider used affects maximal current available at the output, output resistance and makes a constant load that drains the battery, lowering the voltage level.

Precision voltage reference – modern integrated voltage references have low temperature coefficient (TC), high accuracy, low noise and excellent line regulation. REF01 [3]. is an industry standard +10 V reference, with TC of 8.5 ppm/°C and 0.3% accuracy. For high accuracy applications, better references are needed, like MAX6126 [4] with 0.02% accuracy and TC of 3 ppm/°C.

Direct voltage standard – a self-contained voltage reference module with several fixed voltages, like Fluke 732B [5] with accuracy better than 0.0002% and TC below 0.1 ppm/°C.

The main disadvantage of a precision voltage reference is its single fixed output voltage. If a programmable TVS is needed, a new set of problems arise. A precise variable trimmer, set up as voltage divider, must be added to the output of a precision voltage reference in order to obtain variable output voltage. This affects its output resistance and introduces higher TC due to the resistive material used in resistors and trimmers. As the mechanical nature of a trimmer makes it susceptible to mechanical stress and minute movements of its internal parts, the precision is also affected by the mechanical stress that is always present when a device is used in the field. In order to determine the voltage at the output, a high precision digital voltmeter must be used in the setup. The standard solution to this problem is a voltage calibrator with wide range of stable output voltages.

A laboratory calibrator is not a portable device intended to be used in the field, due to its weight and sensitivity. Portable calibrators are available, with sufficient accuracy, temperature stability but with high cost and the need for the mains power supply. Hand-held portable calibrators are compact and battery-operated, representing the best solution for the filed calibrations. Low-cost compact calibrators have low accuracy (0.1%), while high accuracy process calibrators, like Fluke 715 [6] with 0.015% accuracy have high prices (over $1000).

Producing a high accuracy, low TC, portable and low-cost custom TVS solution is described in the paper.

2 Semi-Automated Plating Plant

Electroplating of items with complex shapes is performed with a system of several electrodes, instead of just one. This enables better control of the plating thickness over the entire item, with minimum losses. Each electrode is controlled separately, resulting in high precision products, but with much higher cost than for the single-electrode process.

A semi-automated multi-electrode electrolysis process plating plant from early 1970's is analyzed. Plating process is controlled by a Work-Stations (WS), Fig. 1. There are three identical WS in different facilities across the plant. Each WS has a set of four modules (M_1 to M_4), with each module having an analog reference voltage input U_{REF}, output analog control voltage U_{CON} and a precise 20-turn vernier correction potentiometer P_k with 200 discrete steps available.

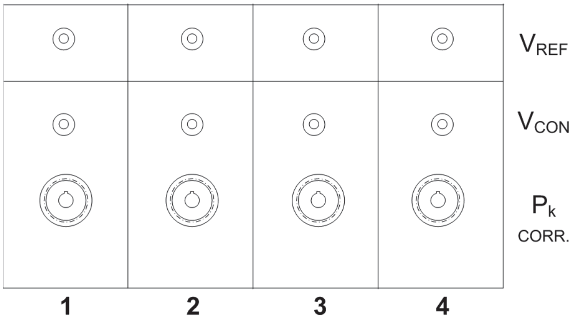

Fig. 1 – *A Work-Station with four modules.*

The description of the WS functions is given in Fig. 2.

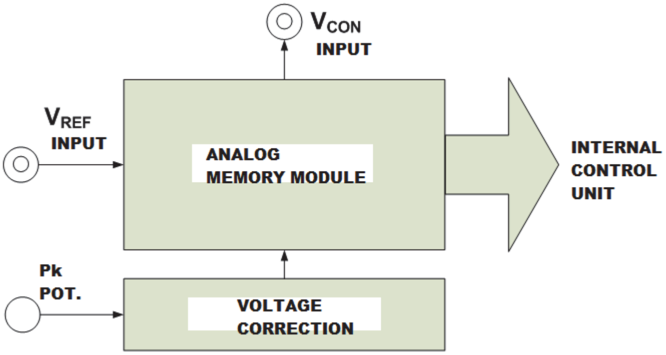

Fig. 2 – *WS block diagram.*

Input voltage is routed to the analog memory module, where voltage is stored with sample-and-hold type of circuit. This voltage is later used for the rest of internal control circuitry that controls plating electrodes. Variations of stored voltage were expected due to the low-performance parts available at the time of production, so precise vernier potentiometer was provided for manual correction of the voltage in a narrow range. An accurate voltmeter was needed to control the exact voltage stored in analog memory, available at the U_{CON} output.

Input voltage range U_{REF} is 5 V to 10 V, selectable in 1 mV steps. Manufacturer provided tables that relate exact voltage to the specific performance of an electrolysis electrode, as needed for precision plating process. Due to the degraded performance of the original circuit, analog memory can have drift up to ±20 mV from the input U_{REF}, but once it drifts, it stays at that level for a prolonged period of time without further drifting, unless input voltage is changed.

In the original setup, the system had mobile voltage standard mounted on a trolley. It had a bank of four programmable analog voltage storages and a high-accuracy digital voltmeter. The voltages are programmed with dual-channel voltage calibrator Bradley with range 0 to 10 V and declared error below ±0.01%. From the calibrator, standard was transferred to WS, U_{REF} was set, and then U_{CON} was corrected using the voltmeter and correction vernier potentiometer. The original mobile standard was lost, and the original calibrator, while fully operational, is not easily moveable as it weights around 35 kg.

Main task is defined – a new, highly mobile, transfer voltage standard must be constructed with an appropriate precision instrument.

2.1 Main considerations

It is requested that the plant remains in the hold for the shortest possible time during the calibration. Currently it is around 90 minutes, considerable time if it is done on daily basis. This means that three separate voltage standards are needed in order to enable parallel calibration of all WS, reducing the total calibration time. Best solution would be to obtain three full sets of commercial voltage standards/calibrators with accurate voltmeters with error below 0.02%, [2, 7]. This represents the highest cost solution regarding the equipment, but the project cost was set to 1/20 of the commercial solution. Autonomy of the standard must be at least 2 hours to enable calibration in the whole plant. Large area of the plant with different facilities results in large temperature fluctuations from facility to facility, so the standard must have low temperature coefficient. Finally, the system must be very simple to use, as the training of designated operators for the industrial grade of instruments is lengthy and have high costs. It is preferred that the system could be used by any worker in the plant, with minimal training, so indicators must be used instead of the complex instruments. The exact result of voltage measurement then is not needed, we just need the information if the voltage is in the right range of given values.

It is know that temperature variation is ±5 ºC over the entire plant, that humidity is low and controlled, and that each WS is in a separate facility.

3 Theory of Operation

The simplest form of a dc voltage storage is a capacitor. Its main problem is finite isolation resistance R_{ISO}, resulting in self-discharging current when capacitor is outside of a circuit, [1, 8]. High rate of self-discharging makes a standard capacitor inapt for long-term voltage storage. Fig. 3 presents a standard equivalent capacitor model, with its serial and parallel resistances R_{ES} and R_{ISO}, where $R_{\mathrm{ES}} \ll R_{\mathrm{ISO}}$, [1, 9, 10].

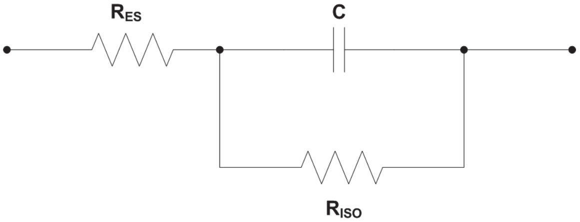

Fig. 3 – *An equivalent capacitor model.*

Standard capacitor discharge function is given in (1). For a capacitor with capacitance C, time t is needed for voltage to drop from U_0 to U_1 when discharged through resistance R. When R is just the capacitor isolation resistance R_{ISO}, then (1) models the self-discharge function of a capacitor.

$$t = CR\ln\left(U_0 / U_1\right). \tag{1}$$

Self-discharging time depends on the capacitor type and value, ranging from several seconds to several minutes. Condition for the transfer voltage standard is to have voltage tolerance of ±0.02% during two hours after charging. Using (1), a standard electrolytic 100 μF capacitor, with R_{ISO} below 1 MΩ [11], will discharge to 10% of initial voltage during 230 s. The voltage drop of 0.02% for the same capacitor takes only 20 ms. This illustrates how a standard capacitor cannot be used as a precision voltage transfer standard. The best quality commercially available low self-discharge capacitors are teflon and polypropylene (PP) film capacitors, [9, 12]. A typical PP film capacitor made by Panasonic has $R_{\mathrm{ISO}} > 30$ GΩ, [13], giving around 6 seconds of stable voltage level before it falls below needed 0.02% tolerance.

Capacitors that are charged constantly over a prolonged period of time exhibit an effect known as *dielectric absorption*, where capacitor regains a part of its charge even when discharging cycle has begun. This is a well-known effect observed in sample-and-hold circuits, where voltage on the capacitor during the “hold” state increases instead holding its value, introducing an error.

This effect was of high importance in circuits with military specification, so much so that there was a military standard that specified measurement method for dielectric absorption (DA) [14]. Dielectric in the capacitor without an external load exhibits characteristics of a battery after a longer period of charging of 10 to 60 minutes (*soaking,* [12]). This results in delayed start of exponential self-discharging described in (1). While capacitor actually is discharging, this effect is opposed by the effect of charge increase induced by DA, effectively resulting in a constant voltage held by the unloaded capacitor [9 – 11].

Fig. shows the circuit for measurement of *DA* coefficient given as in (2):

$$DA = \left(U_2 / U_1\right) 100\ \% . \qquad (2)$$

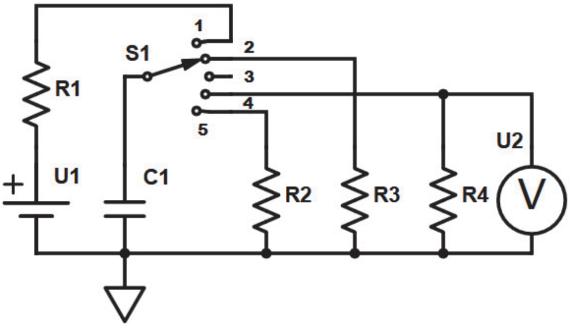

Fig. 4 – *DA coefficient measurement circuit.*

Measurement procedure is given as a sequence of positions of the switch S1. In position 1, C_1 is charged for 15 minutes with initial dc voltage U_1. R_1 limits inrush current to 50 mA. In position 2, C_1 is discharged via R_2 = 50 Ω for 10 seconds. In position 3, C_1 is floating for 15 minutes, in order to allow time for DA effect. In position 4, voltmeter V measures regained voltage U_2. Voltmeter input resistance R_4 must be at least 10 GΩ. After the measurement, capacitor is grounded via R_2 = 1 kΩ in position 5.

Voltage stability on the charged capacitor is tested with circuit given in Fig. 7. Panasonic PP film 1 μF capacitor is charged (soaked) during one hour at 10 V. After removal of the charging circuit, voltage on the capacitor was monitored during next 24 hours. During that period, voltage decreased for 5 mV or 0.05%, confirming assessments given in [12] and [11]. The experiment was repeated for 30 times for statistical reasons, with similar results. In Fig. 5, capacitor voltage is plotted over 24 hours, measured every hour, giving approximately linear decrease (instead exponential).

Discrepancy between theoretical and practical values cannot be explained only by DA. The main source of this difference lies in the fact that R_{ISO} is tested only with high voltage, 500-1000 V during one minute. The figure given in the capacitor datasheet is the result of this test, not representing typical low voltage working conditions where R_{ISO} is much higher for modern PP and teflon capacitors. More realistic figure is hard to be determined, as self-discharging current through isolation is at the order of several tens of femtoamperes for voltages below 50 V, presenting a difficult task for practical measurements [7], [9 – 11].

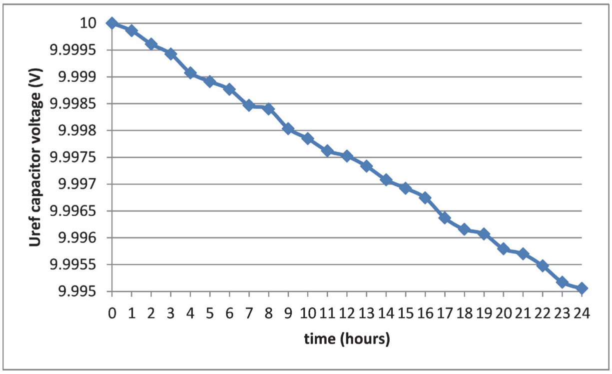

Fig. 5 – *The mean of 30 measurements of* 1 µF *PP film capacitor voltage measured over one day.*

For the voltage range 5–10 V of U_{REF}, identical results are obtained. To assure repeatability of the results, the test was repeated daily over 5 day period on a set of 5 capacitors. Results showed that soaking time can be cut from 1 hour to just 10 minutes with similar results of voltage decreasing for 0.03% during 5 hour period, plotted in Fig. 6. This is well above needed 2 hours for the transfer standard. Teflon film capacitors have even higher isolation resistance, but with the price 5-20 times of the PP capacitor, they were not considered in this application.

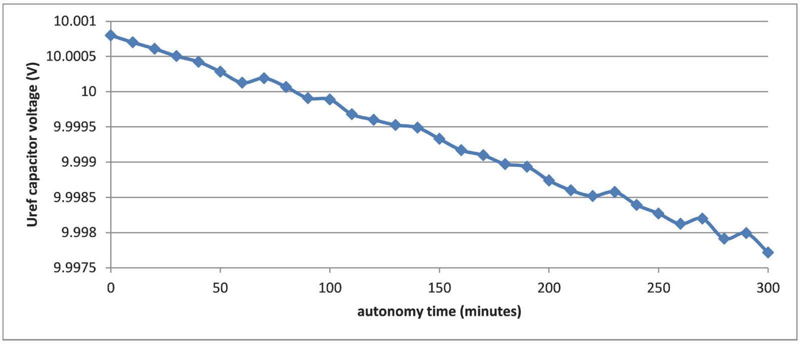

Fig. 6 – *A* 1 µF *PP film capacitor voltage after 1 hour soaking measured over 5 hours.*

Next task is to transfer voltage from the capacitor to the analog memory module and measure it, without affecting the charge. As the capacitor discharges via the input resistance of the connected voltmeter, standard digital multimeter (DMM) with 10 MΩ input cannot be used. Only high-end laboratory DMMs have 10 GΩ input impedance for dc voltages, and even this order of magnitude allows for only several seconds of measurement, (1). Similar problem is present when connecting C to U_{REF}, the input of an obsolete operational amplifier (opamp) with input impedance below 10 MΩ. The most practical solution is to insert a voltage buffer in front of the DMM. Fig. 7 shows the LT1169 [15] unity gain JFET voltage buffer with input impedance over 10 TΩ. Measured voltage now is U_{OUT} at the buffer output, not U_{C} present across the capacitor. U_{OUT} has opamp voltage offset added, but this is small voltage constant in time, and it is calculated in the final design. Declared offset value is 0.6 mV, but in reality, it is 10 times lower when opamp is battery operated.

The buffer output is also connected to U_{REF} input. High input impedance of LT1169 enables 33 minutes of measurement until capacitor loses more than 0.02% of the initial voltage.

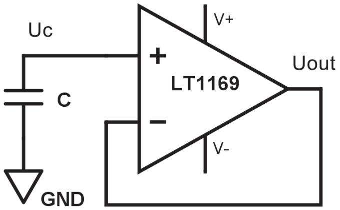

Fig. 7 – *Unity gain buffer for the capacitor voltage.*

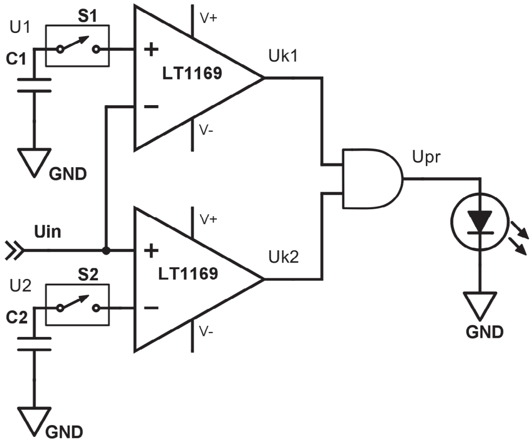

Fig. 8 – *Precise window comparator.*

We can take two capacitors, and charge one with voltage equal to the upper end of allowed U_{REF} range i.e. $U_1 = (U_{\mathrm{REF}} + 0.02\%)$, and other to the bottom end of the range $U_2 = (U_{\mathrm{REF}} - 0.02\%)$. Now, the measurement of the absolute value of the control voltage U_{CON} is not needed anymore, as we only need to check the relative value of U_{CON}. If $U_1 > U_{\mathrm{CON}} > U_2$, the LED indicator is switched on, and if not, correction potentiometer P_k must set until the indictor is switched on, [1, 2, 16]. This is realized with the circuit shown in Fig. 8, a precise window comparator [1], with its transfer function shown in Fig. 9.

Capacitors C_1 and C_2 are charged during 10 minutes to reference voltages U_1 and U_2, respectively. These two voltages are brought to inputs of two LT1169 opamps connected as voltage comparators. Switches S_1 and S_2 are switched on only during the measurement cycle in order to minimize discharge time. Due to the large input impedance of LT1169, capacitor voltage remains in allowed range over several hours of measurement when switches are connected. Voltage U_{CON} is connected to the inverting input of upper and noninverting input of lower comparator. Voltages U_1 and U_2 now represent voltage upper and lower thresholds for the comparators, respectively. While $U_{\mathrm{CON}}<U_2$, top comparator output U_{K1} is in high logic state, while bottom comparator output U_{K2} in low state. For $U_{\mathrm{CON}}>U_1$, U_{K1} is low and U_{K2} is low [1]. Only when $U_1>U_{\mathrm{CON}}>U_2$, both comparators are in high state (voltage U_{PR} in Fig. 9), giving high state at the AND logic gate output and switching on a LED, indicating that measured voltage is in the set range.

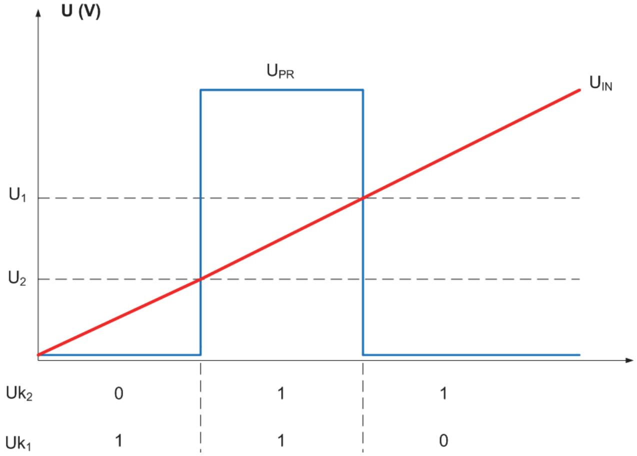

Fig. 9 – *Window comparator transfer function.*

PP film capacitors are susceptible to ambient humidity variances, [9, 11]. The plant has controlled ±1 % humidity variation, eliminating it effect on the measurements. Ambient temperature has ±5°C variation over all the plant facilities. Measurements confirm that this temperature variation has no effect on given PP capacitor self-discharge time.

4 The Prototype

The first prototype used four precise voltage references REF01 [3] with precise 10-turn trimmers, set by a high-accuracy DMM. Large temperature variation in the plant and mechanical stress of the trimmers during the transfer in the field, resulted in voltage drift of 0.3% to 0.5%.

Fig. 10 shows the circuit of the final transfer voltage standard prototype. It has four pairs of capacitors, needed for four programming voltages for a WS. Each Double Pole Single Throw (DPST) switch S_1-S_4 selects one pair of voltages needed for M1-M4 in a WS.

Circuit is powered by four 9 V batteries, connected to supply symmetrical ±18 V to the opamps.

Buffer output voltages drift less than ±0.03% over a 5 hour period, as a cumulative effect of opamp noise and offset, voltage drop in cables and contacts, variances of capacitor characteristics, [1, 7, 17].

U_{PROG} inputs are used for charging capacitors at the reference voltages. HEF4011B is a standard NAND logic gate [18], connected as an equivalent AND gate (NAND and an inverter). A LED is used for the indicator (OK). U_{OUT} is the output for programming WS U_{REF} input. U_{IN} is the voltage input for WS U_{CON}. S_0 switches on and off the battery voltage supply of the TVS.

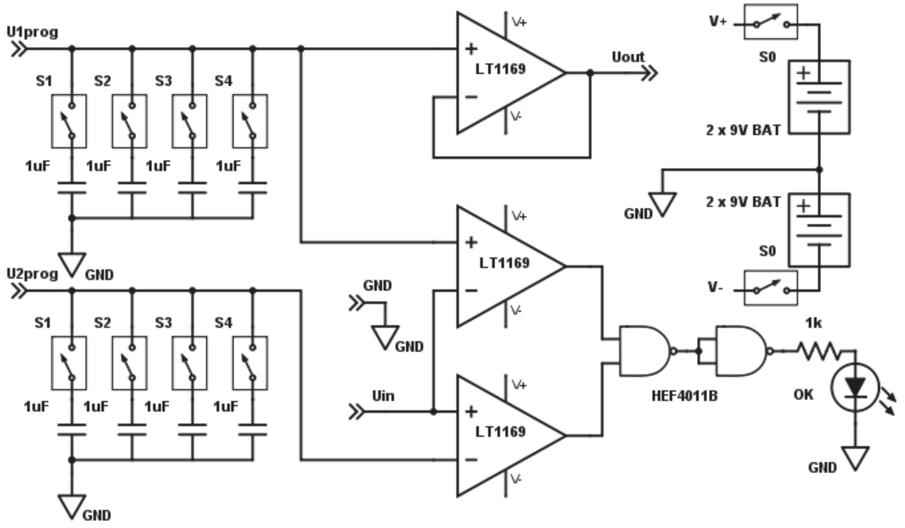

Fig. 10 – *Electric circuit of the transfer voltage standard.*

Operation procedure

First, TVS is programmed by the voltage calibrator. Both poles of the switch S_1 are closed, dual-channel voltage calibrator is set to output first pair of U_1 and U_2, and then connected to $U_{1\mathrm{PROG}}$ and $U_{2\mathrm{PROG}}$, respectively. After 10 minutes of soaking, S_1 is switched off and the cycle repeated for S_2, S_3 and S_4. After 40 minutes, all 4 pairs of voltages are programmed in the TVS (leaving more than 4 hours for further deployment).

When brought to the WS, circuit is switched on with S_0. U_{OUT} is connected to M1 U_{REF}. S_1 is switched for five seconds. Then, U_{OUT} is disconnected, and U_{IN} connected to M1 U_{CON}. S_1 is switched on, correction potentiometer Pk1 is manipulated until the LED indicator is switched on. The procedure is repeated for other modules of the WS.

This procedure takes less than 10 minutes for all WS. Programming voltages are usually very close to previous settings, so there is only small correction needed.

5 The Final Results

Table 1
Preview of the TVS results.

	expected	accomplished
Calibration time needed for the whole system	< 1.5 h	10 minutes
U_{REF} voltage tolerance	±0.02 %	±0.03 %
TVS autonomy	2 hours	5 hours
Temperature coefficient	0 %	~ 0 %
Price compared to the commercial solution	1/20	1/100
Simple usage	Yes	Yes

Table I shows the comparison of expected and accomplished goals for TVS prototype. All conditions are met successfully, with voltage tolerance above set range but over 2.5 times longer time period.

The assessment of the price is done based on a need for the high accuracy voltage calibrator Fluke 715 and the high accuracy industrial multimeter Fluke 87 V (needed to measure U_{CON}) [20], where a single calibrator/multimeter set costs over $2000 (without the shipping costs). The TVS prototype described here has 0.03 % accuracy compared to 0.015% of the Fluke 715, at a hundred times lower price, making this solution highly cost effective. The accuracy of TVS is sufficient for the intended purpose, while the main request of low-cost device based on the standard off-the-shelf components is realized in full. Short time from the initial design to the full working prototype (two weeks) is also a significant factor in the final assessment, comparable to the time needed for calibrator/multimeter set to be delivered after the initial purchase (up to 30 days).

6 Conclusion

Simple PP film capacitor used with high input resistance opamp can be used as a TVS for calibration in the field, outside of a laboratory where temperature variances can affect regular voltage standards. Several months of successful TVS use in the field confirm that simple and cheap solutions could be implemented when such constraints are present. This solution has very effective cost/performance ratio, given in [2, 19], while using very simple technology based on circuits given in [1, 8].

The plant where TVS is implemented is obsolete, but this example illustrates that not always the most modern solution is needed or possible, when cost is the main constraint. Modern solution would implement a PLC or IoT system, but the industrial electrical engineering asks for creative solutions to unique problems with minimal resources.

7 Acknowledgement

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