Simplification of null method measurement system to build a standalone DC voltage standard traceability system in the SNSU - BSN electrical metrology laboratory

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Abstract. Since 1987, electrical laboratory of SNSU was built a traceability capability of DC voltage unit from PJVS up to two Multifunction Calibrator instruments. Therefore, the dissemination accuracy was performed gradually from PJVS to two multifunction calibrator through a standard cell instrument. The two units of multifunction calibrators instruments are used as working standards instrument and should be maintained its traceability. One of the multifunction calibrator (MCS) instrument that is traceable to the standard cell instrument will be disseminated it accuracy to the other multifunction calibrator (MCU) instrument was done in these research. A potentiometer principle was basically used as a subtractor system that subtract the MCS value from the MCU value. Uncertainty analysis is carried out in this paper to validate the characteristics of the method against the NULL method based on the error number (En) reaching -0.1

1. Introduction
As a national laboratory, the electrical laboratory of SNSU – BSN is taken responsible in maintaining the accuracy of DC voltage standard [3]. More than 200 electrical laboratories in Indonesia need this calibration service. This service is handled by unbroken chain of calibration (traceability) which is provided in source and meter types such as a Programmable Josephson Voltage System (source) [2], five standard cells (source), two multifunction calibrators (source), and a reference multimeters (meter). At the moment, the PJVS accuracy is maintained by conducting an inter-laboratory NULL comparison with other National Measurement Institute (NMI) such as NMIJ – Japan. The standard cell accuracy which is maintained by PJVS is prepared for the next accuracy dissemination to multifunction calibrator.

Almost all of the calibration services of DC voltage unit received in electrical laboratory of SNSU – BSN is conducted using a working standard. Those working standards are technically supported by two multifunction calibrator that is catagorize as the first MCS more accurate than the second MCU. In order to keep the calibration services affectively in time and budget, a discipline schedule of maintaining accuracy for MCU is need. Therefore, a certain technically support should be prepared by laboratorium in order to avoid the burden of cost and time.

The method of accuracy dissemination from standard cell to the first multifunction calibrator is need a certain technique based on potensio principle. These potensio principle method has been carried out by using a reference multimeter which depend on the known rasio number accuracy from...
1:1, 1:10 and 1:100 [1]. The potentiometric method calibration system is not only used as a mathematical ratio of NULL, it can also be implemented as a subtraction ratio. So that the accuracy of the second multifunction calibrator that have multirange can be obtained by a subtraction comparison method.

Through this study, the subtraction comparison method whose accuracy is disseminated by a "NULL" comparison method has been valid to implemented. The validation process that is technically implemented has been realized using En numbers. En number is an error analysis method that compares the quality of measurements obtained from the NULL comparison method as the standard method and the subtraction method as the MCU (System Under Calibration) method. In the future the application of this validated measurement method can be used to declare an independent traceability system for DC voltage units in the SNSU - BSN electrical laboratory.

2. Theory

Standard measurements of voltage alter the circuit being measured, introducing uncertainties in the measurements. Voltmeters draw some extra current, whereas ammeters reduce current flow. Null measurements balance voltages so that there is no current flowing through the measuring device and, therefore, no alteration of the circuit being measured. Null measurements are generally more accurate but are also more complex than the use of standard voltmeters and ammeters, and they still have limits to their precision. In this manuscript, we shall consider a few specific types of null measurements, because they are common and interesting, and they further illuminate principles of electric circuits.

2.1. The null method measurement system

When an electric circuit forms a closed circle according to Ohm's law, an electric current will occur. The emergence of current flow is because there is a process of loading on the components of the electrical component itself and this confidence is called bias current. The direction of current flow is determined by the position presentation of standard cells polarity (source) in the circuit. It is characterized as shown in the Figure of 1b and 1c where the current direction is change into counter clockwise from the original circuit Figure 1a. Not the case if you change the position of the polarity of the voltmeter as shown in Figure 1b. This condition occurs because the nature of the current flow in the circuit will occur with a certain polarity direction if there is a voltage source with a certain polarity in the electric circuit. Although the current flow is the subtraction current from several voltage sources installed with opposite polarity.

![Figure 1](image_url)

**Figure 1.** (a) Forward measurement, (b) Reverse measurement, (c) Reverse measurement

For measurement purposes, the series of measurements formed according to Figure 1a are Forward measurements. Furthermore, Figure 1b, 1c can each be translated as a measurement with reverse polarity (Reverse measurement) based on $V_{RM}$ replacement polarity and standard cell replacement, respectively. Each Forward measurement and Reverse set of measurements can be derived into two equations as follows,
\[ E_X + V_{RMM-F} - E_S = 0 \]  
and,

\[ E_X - V_{RMM-R} - E_S = 0 \]

where,

- \( E_X \) is a standard cell under calibration,
- \( E_S \) is a standard cell reference,
- \( V_{RMM-F} \) is the voltage measured by Reference Multimeter (RMM) in Forward measurement,
- \( V_{RMM-R} \) is the voltage measured by Reference Multimeter (RMM) in Reverse measurement.

The value of the loop current that occurs in the measurement circuit must not be affected during the measurement process. These conditions are met by making Forward and Reverse measurements which when added mathematically will produce a value that equal to the current of the loop. Ideally this loop current is equal to zero, so, there is no subtraction value between standard cell reference and under calibration.

Based on the measurement circuit analysis the current loop is equal to the addition of Forward and Reverse measurements. Loop current values can be obtained based on the analogy of the measurement process in the form of a sum between equations (1) and (2) as shown bellow,

\[ \frac{V_{RMM-F} - V_{RMM-R}}{2} = E_X - E_S \]  

2.2. Multifunction calibrator calibration using a subtraction method measurement

Direct method of measurement is a simple method of measurement, in which the value of the quantity to be measured is obtained directly without any calculations. This method is most widely used in a calibration laboratory for services. The measurement accuracy of this method is depend on human insensitiveness in making judgment. A subtraction measurement method which is implemented in this research is the most effective one need to develop an independent traceability in an electromagnetic (EM) Laboratory of SNSU – BSN as shown in Figure 2.

The dotted lines show that the calibration was carried out before the research, which was calibrated abroad. The solid line shows that the calibration can be done internally. The SNSU - BSN EM Laboratory can carry out maintenance of the accuracy of the standard DC voltage independently after this research. Thus, the time needed for the overseas calibration process which can be more than 3 months can be significantly reduced. And budget funds needed for the external calibration process can be saved 100%.

Measurement of the NULL method based on the potentiometer method experience is very suitable for the process of dissemination of accuracy with subtraction measuring points. While the multimeter method is very suitable for the process of dissemination of accuracy with the same measurement point and there is no loss ratio. The reference multimeter (RMM) used for measurements in this study meets the technical requirements because it has a higher ability of stability. So that the calibration implementation does not need to pay attention to the level of accuracy of the RMM because it can already be represented by its resolution.
The measurement system for the subtraction method carried out in this study involves 3 main equipment namely a DC F-5700A (MCU) standard voltage source device [8], a calibrated DC voltage source device F-5720A (MCS) and a standard DC voltage measuring instrument F-8508A (RMM) [9]. RMM measuring devices have 2 input terminals, each of which is in front of the panel (F) and behind the panel (R). Both voltage sources have the ability to generate DC voltages up to 1000 V.

Refers to the equation 1 and 2 that the Forward (F) measurement and the Reverse measurement are realized respectively based on the exchange of the MCS position to the position MCU and vice versa. Or in the form of a simple equation when Forward standard cell position measurements based on Loop currents form MCS - MCU and on Reverse measurements are $E_X - E_S$. 

**Figure 2.** Independent traceability of DC voltage standard in EM laboratory of SNSU - BSN

**Figure 3.** The circuit of measurement systems based on the NULL method of the multifunction calibrator
3. Data Analysis and Discussion

NULL measurement method is more precise compared to other measurement methods because that in a measurement system other than the NULL method allows the accuracy of non-zero readings can be "more influenced" by many factors [6]. The Null method works by making a reference signal that is the same as the signal being measured. It is easy to make a reference signal match the unknown exactly, but the absolute accuracy of the measurement (relative to the accepted standard) depends on how accurate / stable the reference source is and / or the ability to measure its output accurately. The subtraction is subtle (fine), but important.

There are two main benefits of the null-balance measurement method. The first is that the quantity measured is not affected in any way by measurement when the system is balanced; that is, there is no "loading" effect. The second is that as long as the measurement is always done at the same point on the reading device (meters), any nonlinearity on the reading device itself does not affect the measurement at all. The only requirement is that the reader must have good "repeatability", meaning that it always returns to the same point at the measured quantity, regardless of previous history. In most cases the measuring instrument influences the measured system which results in an error. Sometimes it is not possible to calculate that error and correct the result.

In general, to reach zero is much easier and more precise than if you want to reach the peak value. Achieving a peak accuracy means, for example, being able to know the subtraction in units between 10,000 and 10,001, while reaching the exact zero means to know the subtraction between 0,000 units and 0.001 units. Errors affect the previous measurement more than the measurement later.

3.1. Measurement Procedure

NULL measurements are used to reduce uncertainty at the measured voltage [4]. From the explanation above it can be stated that a null measurement balances the voltage so that no current flows through the measuring instrument that will interfere with the measurement. Standard measurements of the voltage change the circuit, introducing numerical uncertainty and the Voltmeter draws extra current. The Null measurement balances the voltage, so that no current flows through the measuring device and the circuit does not change.

The equilibrium condition (measurement balances) of the NULL method measurement circuit in this study was carried out by adjusting the output value of the standard voltage source (MCS) to the designation of a minimum value multimeter (Reference Multimeter) or zero. The minimum value of the multimeter designation is the resolution value that can be set as the resolution uncertainty value. Each measurement corresponds to the specified measurement point measurement point twice, namely FORWARD and REVERSE measurements (see Figure 4). Retrieval of data at each point of measurement carried out 5 times the measurement. Thus, each measurement point is carried out 10 times (n) measurements.

![Figure 4. Measurement overview of NULL method of multifunction calibrator measurement system](image)

According to Kirchoff’s series of measurements the Voltmeter-based NULL method produces an equation,

\[
(E_{\text{MCS}} + \Delta_{\text{MCS}}) + (V_{\text{RM}} + \Delta_{\text{RM}}) - E_{\text{MCU}} = 0
\]

(4)
where,
$E_{MCS}$ is a standard instrument DC voltage value generated by Fluke 5720A (V),
$\Delta_{STD}$ is a standard instrument DC voltage correction (V),
$E_{MCU}$ is a calibrated DC instrument voltage value generated by Fluke 5700A (V),
$V_{RM}$ is the subtraction value between $E_{MCS}$ and $E_{MCU}$ which is read by the Reference Multimeter measuring instrument (V), and
$\Delta_{RM}$ is a calibrated DC instrument voltage correction (V)

The mathematical model of this set of measurements expressed as in the above equation produces a source of measurement uncertainty which consists of 3 main Components namely those derived from standard instruments ($E_{MCS}$), MCU instruments ($E_{MCU}$) and measuring instruments ($V_{RM}$).

The FORWARD measurements shown in Figure 4 are the positions where both the standard source instrument and the source are calibrated respectively as shown. In electric circuitry form, such a position explains that the output of a standard source instrument is connected to the Reference Multimeter terminal which is on the front panel (FRONT PANEL) and the source instrument calibrated on the back panel (REAR PANEL). To continue the measurement of REVERSE, the position of the standard instrument and the calibrated instrument are exchanged by adjusting the reverse circuit.

![Figure 5](image1.png) **Figure 5.** 1 V measurement data’s of Subtraction method

![Figure 6](image2.png) **Figure 6.** 10 V measurement data’s of Subtraction method

![Figure 7](image3.png) **Figure 7.** 100 V measurement data’s of Subtraction method

![Figure 8](image4.png) **Figure 8.** 1000 V measurement data’s of Subtraction method
### Table 1. Forward and reverse measurement result in the subtraction measurement

| Measuring Point (V) | MCU FORWARD (V) | MCU REVERSE (V) | MCS Reading (V) | MCU Value (V) |
|---------------------|-----------------|-----------------|-----------------|---------------|
| 1                   | 0.9999714       | 0.9999700       | 1.0000000       | 1.0000007     |
| 10                  | 10.000025       | 10.000025       | 10.000000       | 10.000000     |
| 100                 | 100.00008       | 100.00012       | 100.00000       | 99.99998      |
| 1000                | 999.9996        | 1000.0009       | 1000.0000       | 999.9994      |

### Figure 9. 1 V measurement data’s of NULL method

### Figure 10. 10 V measurement data’s of NULL method

### Figure 11. 100 V measurement data’s of NULL method

### Figure 12. 1000 V measurement data’s of NULL method

### Table 2. Forward and reverse measurement result in the NULL comparison measurement

| Measuring Point (V) | MCU FORWARD (V) | MCU REVERSE (V) | MCS Reading (V) | MCU Value NULL (V) |
|---------------------|-----------------|-----------------|-----------------|-------------------|
| 1                   | 0.9999972       | 0.9999705       | 1.0000000       | 1.0000134         |
| 10                  | 9.999998        | 10.000024       | 10.000000       | 9.999987          |
| 100                 | 100.00015       | 100.00003       | 100.00000       | 100.00006         |
| 1000                | 999.9950        | 1000.00035      | 1000.0000       | 999.9973          |
3.2. Data Analysis

The subtraction in DC voltage between MCU and MCS can be obtained by deriving the Null method equation as follows,

\[
\frac{V_{RMM-F} - V_{RMM-R}}{2} = E_x - E_s
\]

that can be assumed into the new variables based on the measurement data variables to become,

\[
\frac{V_{RMM-F} - V_{RMM-R}}{2} = E_{MCU} - E_{MCS}
\]  

(5)

In this study it will be proven that the application of the Subtraction measurement method meets the metrological principle by verifying it with the NULL measurement method based on the validation process of En (Error number). According to the application of Subtraction equation measurement above, it can be simplified into,

\[
E_{MCU} = \frac{V_{RMM-F} - V_{RMM-R}}{2} + E_{MCS}
\]  

(6)

The equation 6 shows that the Subtraction value is obtained from the reading of F - R where the F is the RMM terminal input located in Front panel and the R behind the panel. Mathematically this subtraction method is satisfied by the equation \( F - R \neq 0 \) with the supply treatment at terminals F and R not adjusted. In the NULL measurement method mathematically fulfilled by the equation \( F - R = 0 \) with the treatment of one of the supplies whether the F or R is set so certain that the RMM shows Zero. The measurement results of each of these methods have been shown as shown in Tables 1 and 2. Both tables can be simplified as shown in Table 3 below.

| Measuring Point (V) | MCS Value (V) | MCU Value\(_{Subtraction}\) (V) | MCU Value\(_{NULL}\) (V) |
|---------------------|---------------|-------------------------------|-----------------------------|
| 1                   | 1.00000000    | 1.0000007                    | 1.000134                    |
| 10                  | 10.000000     | 10.000000                    | 9.999987                    |
| 100                 | 100.00000     | 99.99998                     | 100.00006                   |
| 1000                | 1000.0000     | 999.9994                     | 999.9973                    |

The sources of uncertainty of the NULL measurement system can be derived based on the mathematical model of eq.4 is as follows [5][7],

\[
U_{\text{Total}} = \sqrt{u_{u,MCS}^2 + u_{u,RMCS}^2 + u_{u,MCU}^2 + u_{u,RMM}^2 + u_{u,RRMM}^2}
\]

\[\]  

where,

\( u_{u,MCS} \) is the uncertainty value of the instrument under calibration source ,

\( u_{u,RMCS} \) is the uncertainty value of the instrument standard source,

\( u_{u,MCU} \) is the uncertainty value of the measuring instrument, and

\( u_{u,RRMM} \) is the resolution of measuring instrument.

| Measuring Point (V) | MCS Value (V) | MCU Value\(_{Subtraction}\) (V) | \( u_{u,MCU,Subtraction}\) (V) | MCU Value\(_{NULL}\) (V) | \( u_{u,MCU,NULL}\) (V) |
|---------------------|---------------|-------------------------------|-------------------------------|-----------------------------|-----------------------------|
| 1                   | 1.00000000    | 1.0000007                    | 0.0000048                    | 1.0000134                    | 0.0000049                    |
| 10                  | 10.000000     | 10.000000                    | 0.000044                     | 9.999987                     | 0.000044                     |
| 100                 | 100.00000     | 99.99998                     | 0.000568                     | 100.00006                    | 0.00057                      |
| 1000                | 1000.0000     | 999.9994                     | 0.0059                       | 999.9973                     | 0.00591                      |
3.3. Discussion

The process of carrying out measurements in this study is distinguished in the DC voltage supply variable from the multifunction calibrator. In the process of measuring the NULL method, the DC MCU supply voltage is adjusted MCU that the RMM shows a zero value (close to zero). While the measurement process for the subtraction method, both the supply of DC voltage from the MCU and MCS is fixed at its nominal value. Thus, the two measurement systems have a measurement value based on resolution (significant digit) which refers to the stability of the meter reading (RMM). This means that the source of uncertainty in measuring the RMM resolution of the two measurement methods can be considered to have the same resolution value.

Analysis of the data from this method can be verified by calculating an error number of En that can be obtained by comparing the difference in the measurement results of the two methods respectively Value_{Subtraction} and Value_{NULL}. Then the difference is compared to the difference between the uncertainty value of \( u_{MCUSubtraction} \) and \( u_{MCUNULL} \) measurements. Mathematically can be simplified into an equation like the following,

\[
E_n = (\text{Value}_{\text{Subtraction}} - \text{Value}_{\text{NULL}}) / (\sqrt{(u_{\text{MCUSubtraction}}^2 + u_{\text{MCUNULL}}^2)} )
\]  

This error number has a validity value of \(-1 < E_n < 1\).

By using equation (8) the validation of the measurement of the subtraction method can be obtained by processing the data shown in Table (4) and producing an error number as shown in Table 5.

| Measuring Point (V) | MCU Value_{Subtraction} (V) | MCU Value_{NULL} (V) | Error number (En) |
|---------------------|-----------------------------|---------------------|-------------------|
| 1                   | 1.00000007                  | 1.0000134           | -1.86             |
| 10                  | 10.000000                  | 9.999987            | 0.2               |
| 100                 | 99.99998                    | 100.00006           | -0.1              |
| 1000                | 999.9994                    | 999.9973            | 0.2               |

It turns out that the error number obtained at the 1 V measurement point is smaller than -1. According to equation (7) this condition occurs due to the dominance of the difference in the values of the two V_{DC} multifunction calibrator supply values. This error can be made possible by the process of reading the difference in the RMM measuring instruments. The next possibility could also be caused by the stability of the supply signal from both multifunction calibrators.

4. Conclusion

From the results of this study, a validated measurement system has been obtained so that the electrical metrology laboratory at the Directorate of SNSU - BSN has built an independent traceability system on the DC voltage magnitude from the primary standard to the working standard. Simplification of the measurement system from the null method to the subtraction method is guaranteed its validity based on an error number (En) up to -0.1. Increasing the competency of the measurement capacity of the electrical metrology laboratory services still needs to be improved by monitoring the characteristics of the MCS and special MCUs at the 1V measuring point.

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