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Development of Automatic Calibration System for Solid-State DC Voltage Standards and Its Validation

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Abstract: A manual calibration system for the solid-state DC voltage standard has been established at the National Measurement Standard (SNSU-BSN). The manual calibration was time-consuming, fatiguing, and difficult to collect data. To improve this measurement process, SNSU-BSN has developed an automatic calibration system for solid-state DC voltage standards using programmable software for data acquisition and a low thermal scanner for switching during the measurement. A differential measurement method is performed for automatic calibration system in 1.018 V and 10 V. This automatic calibration system has been validated with manual calibration mode for measurement repeatability in same environmental condition. The result shows that the standard uncertainties of repeatability for automatic and manual calibration at a nominal voltage of 1.018 V are 0.0035 μV and 0.0071 μV, and for a nominal voltage of 10 V are 0.090 μV and 0.038 μV, respectively. The normalized error (En number) values of nominal voltage 1.018 V and 10 V are less than 1, stating that the results of automatic and manual measurements are in good agreement. Therefore, the automatic measurement system can be applied to replace the manual process of measurement at SNSU-BSN since this method is faster and has better uncertainty values.

Keywords: calibration; automatic calibration system; solid-state; DC voltage standard

1. Introduction

In recent years, automation in measurement has been widely applied in metrological and industrial laboratories. This kind of measurement is very important to support quality assurance for the energy sector, especially the photovoltaic (PV) measurement system. The development of PV technology is increasing rapidly and widely used for households, pumping and possible to operate using IoT for monitoring, measuring and controlling load[1-5]. Considering the demand for PV quality assurance is essential, a good infrastructure is needed. The automation enables high-quality performance and reduces operation time in the measurement process. The previous study has reported programmable instruments for digital multimeter calibration and source calibration[6-10]. Several manufacturers have created software to perform automatic measurement method[11]. Even though the commercial software has been provided by the manufacturer, it was not suitable and less flexible for advanced measurement. Therefore, the development of customizable software is still required to improve the automation of measurement with high accuracy and precision.

In Indonesia, the National Measurement Standard-National Standardization Agency (SNSU-BSN) is appointed to establish traceability for calibration laboratory. For DC voltage quantity, SNSU-BSN maintains the secondary standard, a solid-state DC voltage standard (DVS), which has been calibrated to the Josephson Voltage Standard (JVS) as the primary standard at the International Bureau of Weights and Measures (BIPM). The nominal calibration values of the solid-state (DVS) are 1.018 V and 10 V. The calibrated values of the solid-state (DVS) were then disseminated to another solid-state (DVS) by using manual measurement based on a differential measurement method[12]. This method offered a measurement technique by canceling an offset of both solid-state (DVS). To realize this method, a supporting low thermal scanner was used for switching during the measurement process[13-14].

The goal of this work is to build a fully automatic calibration system for the solid state (DVS) based on the differential measurement method. In fact, the manual calibration process was time-consuming, fatiguing, and difficult to collect data. On the other hand, automatic

calibration can resolve the limitations of manual calibration systems such as reducing time, easy in collecting data, and autopilot measurement. The measurement setup and uncertainty analysis for the manual and automatic measurements are described in this paper. Furthermore, the validation of the developed automatic calibration system is performed by directly comparing manual and automatic measurement in same environmental condition and equipment.

2. Methods

The differential measurement method has excellent accuracy because this method analyzes the voltage disparity between the calibrated Standard (STD) and the Unit Under Calibration (UUC) by canceling an offset out[15-17]. This method consists of two stages of measurement called forward stage and reverse stage[18]. In the forward stage, the calibrated standard DVS (symbolized by S) is linked to UUC DVS (symbolized by X) in series as shown in Fig. 1. In the reverse stage, the polarity of S and X is switched as shown in Fig. 2. The total voltage in close loop circuit is measured by the digital voltmeter (DVM) and the low thermal scanner is applied to switch the polarity without physically changing the connection.

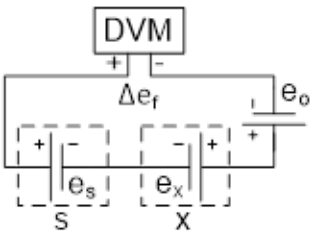

Fig. 1: Forward stage measurement

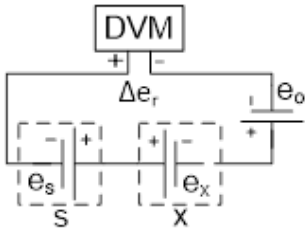

Fig. 2: Reverse stage measurement

Subject to the principle of null balance in close loop sequence, the forward and reverse measurements can be formulated in Eq. 1 and Eq. 2, respectively.

$$\Delta e_f = e_s - e_x + e_o \qquad (1)$$

$$\Delta e_r = -e_s + e_x + e_o \qquad (2)$$

Where Δe_f is voltage difference in forward measurement, Δe_r is voltage difference in reverse measurement, e_s is the standard DVS voltage, e_x is the UUC DVS voltage, and e_o is the total Electromotive force (EMF) of the measurement. The simplification of Eq. 1 and Eq. 2 by eliminating the offset and EMF (e_o) resulted in Eq. 3.

$$e_x = e_s - \frac{\Delta e_f - \Delta e_r}{2} \qquad (3)$$

Assumed that $e_m = \frac{\Delta e_f - \Delta e_r}{2}$, Eq. 3 can be condensed to Eq. 4 and implemented to calibrate UUC DVS known as differential measurement method,

$$e_x = e_s - e_m \qquad (4)$$

Environmental conditions such as temperature (c_T), pressure (c_P), humidity (c_H) and drift (c_d) of the standard DVS are calculated as correction since they affected the measurement as well as resolution (c_{res}) and accuracy (c_s) of the DVM. EMF thermal (c_e) of the measurement system is also evaluated as a correction. Eq. 4 then can be expanded to Eq. 5 to obtain the UUC DVS actual voltage (e_x).

$$e_x = (e_s + c_T + c_P + c_H + c_d) - (e_m + c_{res} + c_s) + c_e \qquad (5)$$

The operating principle of a fully automatic calibration system is schematically presented in the form of an algorithm in Fig. 3. First, setting the address of the DVM and low thermal scanner to make communication and control of the instrument by computer. Second, creating the identities of each DVS that are used in the software as parameters, such as nominal voltage, DVS serial number, and channel number of DVS into the measurement database in the software, then determining the channel pairs to be measured. Third, combining the forward and reverse measurement, where these configurations of the channel pairs are also the parameters in the software, and performing data acquisition 10 times from the DVM.

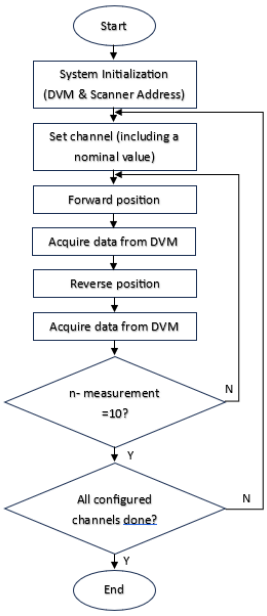

Fig. 3: The flow chart of automatic calibration system

3. Experimental works

The measuring setup for this experiment involves Fluke 7000 as the standard DVS (S) which had been calibrated at BIPM in 2019, Fluke 732B as the UUC DVS (X), Dataproof 320A as the low thermal scanner, and Nanovoltmeter HP 34420 as the DVM. This setup then operated in forward and reverse configurations as shown in Fig. 4 and Fig. 5. In this measurement system, a personal computer (PC) is used to control low thermal scanner and DVM through GPIB/IEEE-488 and deliver data from the DVM to PC.

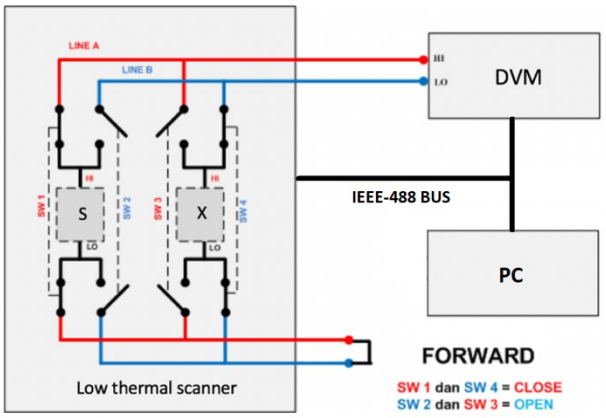

Fig. 4: Measurement configuration for forward measurement

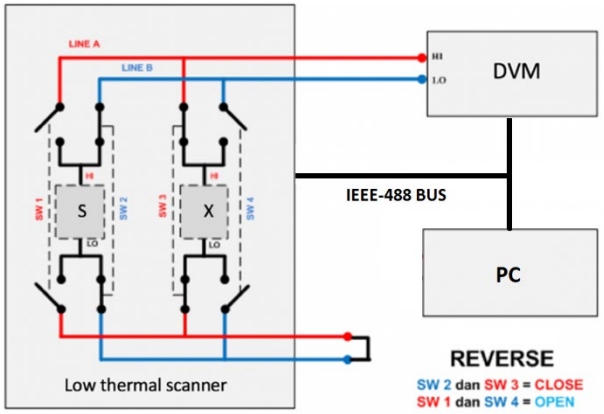

Fig. 5: Measurement configuration for reverse measurement

The low thermal scanner, which is utilized to move from forward to reverse measurement or the other way around, is the main tool in this automatic measuring system. The scanner with an exceptionally low thermal offset is suitable for automation without physically changing the polarity of the DVS. The automatic calibration software is built using Visual Basic based on an algorithm of the differential measurement method which was described in Eq. 1 and Eq. 2 to control the switching step of the low thermal scanner. Based on Fig. 4, forward measurement is constructed by combining switch 1 (symbolized by SW1) and switch 4 (symbolized by SW4) in close condition, while switch 2 (symbolized by SW2) and switch 3 (symbolized by SW3) are in open condition. On the other hand, based on Fig. 5, the reverse measurement is established when SW2 and SW3 are in close position, then SW1 and SW4 are in open position.

The software is designed to manage time delay, control the flow of the measurement process, and ensure all the instruments are following the measurement procedure. In this experiment, the procedure is carried out in three steps: preparation step, measurement step and reporting step. The preparation step includes warming-up, the measurement step involving the measurement process consisting of forward and reverse measurements, and the reporting step collecting the measurement data indicated by DVM then reported into the measurement panel. The measurement panel provided information of time and date, instrument address, measurement point and measurement result as shown in Fig. 6. Furthermore, all measurement results including the measurement points with the configuration of the scanner, and the information of time and date are stored in the spreadsheet for the evaluation.

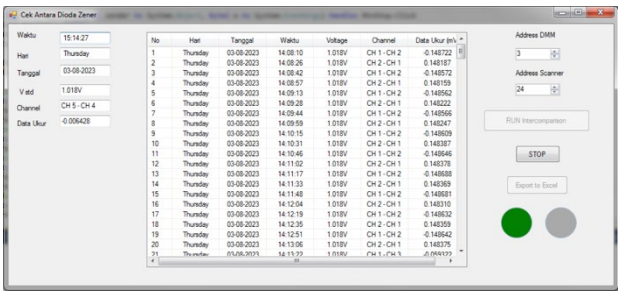

Fig. 6: Measurement panel

The software is then validated to fulfill the requirement requested by standards[19-22]. The validation is conducted to verify the functionality by comparing the automatic and manual measurements[23-25]. The repeatability, known as experimental standard deviation of the mean (ESDM) or a 1σ type A uncertainty, in both automatic and manual modes, are evaluated and compared by doing the measurement under similar environmental conditions and same equipment.

Validation of the automatic measurement system is then performed using normalized error (En number) in Eq. 6

$$E_n = \frac{X_m - X_a}{\sqrt{{u_{X_m}}^2 + {u_{X_a}}^2}} \quad (6)$$

where X_m is the actual value of the manual calibration, X_a is the actual value of the automatic calibration, u_{Xm} is the standard uncertainty of repeatability for manual calibration and u_{Xa} is the standard uncertainty of repeatability for automatic calibration[7].

4. Results and discussion

The measurement data of manual and automatic measurements are shown in Table 1.

Table 1. Measurement data of manual and automatic measurements

Nominal Voltage = 1,018 Volt

Manual				Automatic			
No.	Position		Difference (mV)	No.	Position		Difference (mV)
	Forward (mV)	Reverse (mV)			Forward (mV)	Reverse (mV)	
1	-0,146651	0,146478	-0,146565	1	-0,146742	0,146622	-0,146682
2	-0,146627	0,146491	-0,146559	2	-0,146678	0,146619	-0,146649
3	-0,146627	0,146503	-0,146565	3	-0,146731	0,146617	-0,146674
4	-0,14663	0,146513	-0,146572	4	-0,14668	0,146691	-0,146686
5	-0,146639	0,146526	-0,146583	5	-0,146684	0,146633	-0,146659
6	-0,146627	0,146533	-0,146580	6	-0,146688	0,146637	-0,146663
7	-0,146612	0,146540	-0,146576	7	-0,146698	0,146626	-0,146662
8	-0,146647	0,146537	-0,146592	8	-0,146686	0,146679	-0,146683
9	-0,146633	0,146516	-0,146575	9	-0,146774	0,146675	-0,146725
10	-0,146651	0,146532	-0,146592	10	-0,146782	0,146622	-0,146702
Average			-0,146576	Average			-0,146678
ESDM (u_m)			**0,0035 µV**	ESDM (u_m)			**0,0071 µV**

Nominal Voltage = 10 Volt

Manual				Automatic			
No.	Position		Difference (mV)	No.	Position		Difference (mV)
	Forward (mV)	Reverse (mV)			Forward (mV)	Reverse (mV)	
1	-0,136252	0,136301	-0,136277	1	-0,136939	0,137001	-0,136970
2	-0,136158	0,136416	-0,136287	2	-0,136889	0,137051	-0,136970
3	-0,136228	0,136389	-0,136309	3	-0,136939	0,136952	-0,136946
4	-0,136049	0,136209	-0,136129	4	-0,137015	0,136800	-0,136908
5	-0,136245	0,136577	-0,136411	5	-0,136667	0,136917	-0,136792
6	-0,136495	0,136599	-0,136547	6	-0,136778	0,137032	-0,136905
7	-0,136421	0,136636	-0,136529	7	-0,137014	0,137274	-0,137144
8	-0,136567	0,136896	-0,136732	8	-0,137056	0,136904	-0,136980
9	-0,136988	0,137017	-0,137003	9	-0,137111	0,137280	-0,137196
10	-0,136926	0,136820	-0,136873	10	-0,136988	0,136805	-0,136897
Average			-0,136509	Average			-0,136971
ESDM (u_m)			**0,0897 µV**	ESDM (u_m)			**0,0376 µV**

The detailed analysis of the corrections and measurement uncertainties of the manual and automatic measurements can be found in Table 2 for 1.018 V and Table 3 for 10 V, respectively. The reference certificate is taken from the calibration certificate of standard DVS which has true nominal voltages of 1.017 995 840 V with uncertainty of 10 nV and 9.999 860 76 V with uncertainty of 100 nV, respectively. Some corrections and uncertainties such as temperature, pressure, and humidity are evaluated based on different environmental conditions during the measurement process, while drift is analyzed using calibration history of the standard DVS to Josephson Voltage Standard (JVS) as a primary standard. The repeatability of DVM reading is evaluated from the difference values of ten times repetition for each forward and reverse measurement. The resolution of DVM, the accuracy of DVM and the EMF of the low thermal scanner are estimated based on the instrument's manual specifications. All those components of the reports are calculated manually subject to Guide to the expression of Uncertainty in Measurement (GUM)[26].

Table 2. Corrections and uncertainties of manual and automatic measurements for nominal voltage of 1.018 V

Nominal Voltage of 1,018 V (Manual)

I	II	III	IV	V	VI	VII
Quantity	Estimate	Standard Uncertainty	Probability distribution /method of	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
	xi	u(xi)		ci	ci·u(xi)	vi
Reference Certificate	1,017995840 V	1,0E-08 V	Normal/type B	1	1,0E-08 V	200
Temperature	-0,000000011 V	3,8E-08 V	Normal/type B	1	3,8E-08 V	50
Pressure	0 V	-5,6E-08 V	Rect/type B	1	-5,6E-08 V	50
Humidity	0 V	1,7E-07 V	Normal/type B	1	1,7E-07 V	50
Drift	-0,000001089 V	4,2E-07 V	Normal/type B	1	4,2E-07 V	50
Meter Reading (ESDM)	-0,000146576 V	3,5E-09 V	Type A	1	3,5E-09 V	5
DVM Resolution	0 V	2,9E-08 V	Rect/type B	1	2,9E-08 V	50
DVM Accuracy	0 V	1,2E-08 V	Rect/type B	1	1,2E-08 V	50
EMF Thermal	0 V	1,7E-07 V	Rect/type B	1	1,7E-07 V	50
e_x	**1,0181413 V**	Combined standard uncertainty:			4,9E-07 V	
		Effective degrees of freedom:				89,4
		Coverage factor at 95 % confidence level :			1,99	2,0
		Expanded uncertainty (95% coverage factor):			**0,0000010**	V

Nominal Voltage of 1,018 V (Automatic)

I	II	III	IV	V	VI	VII
Quantity	Estimate	Standard Uncertainty	Probability distribution /method of	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
	xi	u(xi)		ci	ci·u(xi)	vi
Reference Certificate	1,01799584 V	1,0E-08 V	Normal/type B	1	1,0E-08 V	200
Temperature	-0,00000001 V	3,8E-08 V	Normal/type B	1	3,8E-08 V	50
Pressure	0 V	-5,6E-08 V	Rect/type B	1	-5,6E-08 V	50
Humidity	0 V	1,7E-07 V	Normal/type B	1	1,7E-07 V	50
Drift	-0,00000109 V	4,2E-07 V	Normal/type B	1	4,2E-07 V	50
Meter Reading (ESDM)	-0,00014668 V	7,1E-09 V	Type A	1	7,1E-09 V	5
DVM Resolution	0 V	2,9E-08 V	Rect/type B	1	2,9E-08 V	50
DVM Accuracy	0 V	1,2E-08 V	Rect/type B	1	1,2E-08 V	50
EMF Thermal	0 V	1,7E-07 V	Rect/type B	1	1,7E-07 V	50
e_x	**1,018141 V**	Combined standard uncertainty:			4,9E-07 V	
		Effective degrees of freedom:				89,4
		Coverage factor at 95 % confidence level			1,99	2,0
		Expanded uncertainty (95% coverage factor):			**0,0000010**	V

Table 3. Corrections and uncertainties of manual and automatic measurements for nominal voltage of 10 V

Nominal Voltage of 10V (Manual)

I	II	III	IV	V	VI	VII
Quantity	Estimate	Standard Uncertainty	Probability distribution /method of	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
	xi	u(xi)		ci	ci·u(xi)	vi
Reference Certificate	9,999860760 V	1,0E-07 V	Normal/type B	1	1,0E-07 V	200
Temperature	-0,000000700 V	3,3E-07 V	Normal/type B	1	3,3E-07 V	50
Pressure	0 V	-5,5E-07 V	Rect/type B	1	-5,5E-07 V	50
Humidity	0 V	3,3E-07 V	Normal/type B	1	3,3E-07 V	50
Drift	-0,000010608 V	8,4E-06 V	Normal/type B	1	8,4E-06 V	50
Meter Reading (ESDM)	-0,000136509 V	9,0E-08 V	Type A	1	9,0E-08 V	5
DVM Resolution	0 V	2,9E-07 V	Rect/type B	1	2,9E-07 V	50
DVM Accuracy	0 V	1,2E-08 V	Rect/type B	1	1,2E-08 V	50
EMF Thermal	0 V	1,7E-07 V	Rect/type B	1	1,7E-07 V	50
e_x	**9,999986 V**	Combined standard uncertainty:			8,4E-06 V	
		Effective degrees of freedom:				50,9
		Coverage factor at 95 % confidence level :			2,01	2,0
		Expanded uncertainty (95% coverage factor):			**0,000017**	V

Nominal Voltage of 10 V (Automatic)

I	II	III	IV	V	VI	VII
Quantity	Estimate	Standard Uncertainty	Probability distribution /method of	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
	xi	u(xi)		ci	ci·u(xi)	vi
Reference Certificate	9,99986076 V	1,0E-07 V	Normal/type B	1	1,0E-07 V	200
Temperature	-0,00000070 V	3,3E-07 V	Normal/type B	1	3,3E-07 V	50
Pressure	0 V	-5,5E-07 V	Rect/type B	1	-5,5E-07 V	50
Humidity	0 V	3,3E-07 V	Normal/type B	1	3,3E-07 V	50
Drift	-0,00001061 V	8,4E-06 V	Normal/type B	1	8,4E-06 V	50
Meter Reading (ESDM)	-0,00013697 V	3,8E-08 V	Type A	1	3,8E-08 V	5
DVM Resolution	0 V	2,9E-07 V	Rect/type B	1	2,9E-07 V	50
DVM Accuracy	0 V	1,2E-08 V	Rect/type B	1	1,2E-08 V	50
EMF Thermal	0 V	1,7E-07 V	Rect/type B	1	1,7E-07 V	50
e_x	**9,999986 V**	Combined standard uncertainty:			8,4E-06 V	
		Effective degrees of freedom:				50,9
		Coverage factor at 95 % confidence level			2,01	2,0
		Expanded uncertainty (95% coverage factor):			**0,000017**	V

Overall, the comparison results between manual and automatic measurement systems in Table 2 and Table 3 show that the corrections of DVS have different values while the expanded uncertainties have similar values. Detail observation in each component of uncertainty shows a difference in type A uncertainty (repeatability of DVM reading), while the other uncertainty components (type B) do not change significantly. This is because the experiment used the same equipment and similar environmental conditions, so the type B uncertainties were identical. Furthermore, the contribution of DVM

repeatability is insignificant since its value is minor compared to the other uncertainty components.

The results of manual and automatic measurements for nominal voltages of 1.018 V and 10 V are shown in Fig 7 and Fig. 8, respectively.

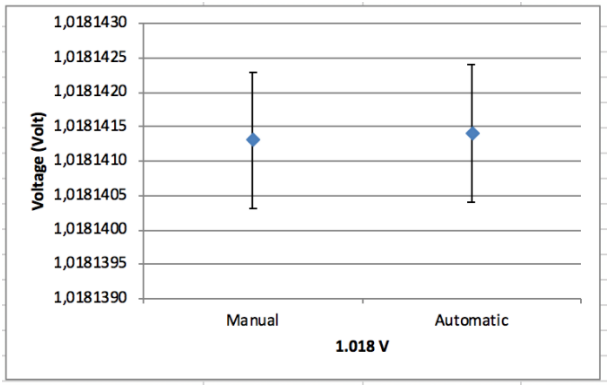

Fig. 7: The results of manual and automatic measurements system at nominal voltage 1.018 V

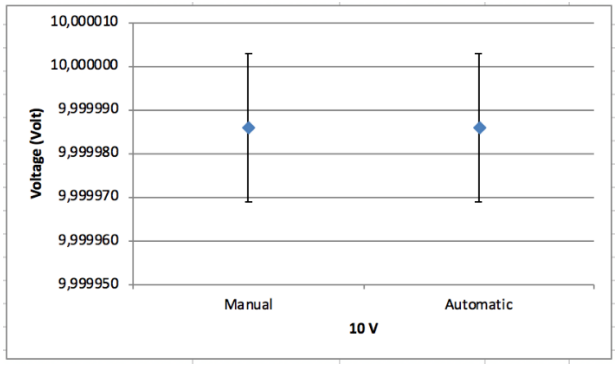

Fig. 8: The results of manual and automatic measurements system at nominal voltage 10 V

Figures 7 and 8 show that the automatic measurement results are quite like manual measurement results. The expanded uncertainties are figured as error bars, and both automatic and manual measurements have similar uncertainty values.

The normalized error (En number) values of nominal voltages of 1.018 V and 10 V are calculated based on Eq. 6 and the result is shown in Table 4.

Table 4. Normalized error of manual and automatic measurement systems at nominal voltages of 1.018 V and 10 V

Nominal Voltage	Manual		Automatic		Normalized Error
	Actual value (Xm)	Uncertainty (U_{Xm})	Actual value (Xa)	Uncertainty (U_{Xa})	(En)
1,018 V	1,0181413 V	0,0000010 V	1,0181414 V	0,0000010 V	0,07
10 V	9,999986 V	0,000017 V	9,999986 V	0,000017 V	0,00

The normalized errors for both nominal voltages are less than 1, therefore the automatic measurement is valid and both manual and automatic measurements have a good agreement with each other.

In term of effectiveness and efficiency analysis, the developed automatic calibration system is faster and more efficient than manual calibration since the automatic calibration can be performed without operator to switch the polarity during forward-reverse measurement process. The automatic method is also applicable to calibrate simultaneously six DVSs, one DVS as standard and five DVSs as UUC. This method utilizes 12 channels of low thermal scanner Data Proof 320A for forward and reverse configurations and each measurement is performed 10 times for repeatability. In total, it consists of 600 measurement steps and requires approximately 172 minutes as shown in Fig. 9 and Fig. 10.

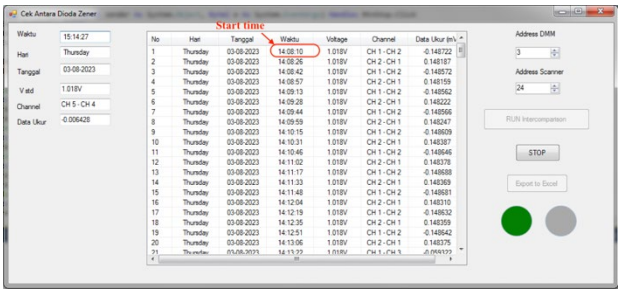

Fig. 9: Start measurement time

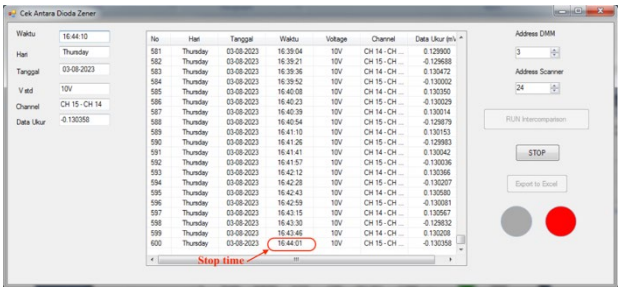

Fig. 10: Stop measurement time

The automatic calibration can run and retrieve raw data measurement by software, whereas the manual calibration depends on the operator to carry out forward and reverse configurations and collect raw data of measurement. The movement of the operator when switching the polarity and potential tiredness of operator when performing 600 measurement steps can contribute to the stability of the measurement.

5. Conclusion

An automatic measurement system has been built for calibrating solid-state DC voltage standard (DVS). It can reduce time during measurement process, simplify the acquisition of measurement data and enable autopilot measurement without physically changing polarity of the DVS whereas the manual calibration depends on the operator which potentially exhausted if performing too many measurement steps and taking longer time.

The comparison of the automatic and manual measurement system is carried out based on a differential method under similar environment conditions and configuration settings. From both automatic and manual measurements, there is a small correction difference of 0.1

μV for nominal voltage of 1.018 V and no correction difference for nominal voltage of 10 V. Furthermore, the automatic measurement system has been validated using normalized error compared to the manual measurement system and the type A uncertainty of each measurement point and mode has an insignificant contribution to the associated expanded uncertainty. The results of the automatic and manual measurements are also in good agreement with each other. Therefore, the automatic measurement system can be applied to replace the manual process of measurement at SNSU-BSN.

However, there remains some future work worth improving. On the one hand, the proposed automatic system still requires a manual process in calculating measurement uncertainty, so it is necessary to develop this software to alleviate this problem. To further improve the automatic measurement system, future research should focus on transforming the measurement result into Digital Calibration Certificate (DCC) to support Metrology 4.0.

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