

# Cross-Needle Analog Meter to Monitor Charge Time for Lithium-Ion Single Cell

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**Abstract**—This manuscript describes a novel cross-needle analog meter whose scale reads out voltage, current, and time remaining to reach full charge. The design is inspired by cross-needle Standing Wave Ratio (SWR) meters that read forward and reverse power. Voltage is displayed on an offset-zero linear scale, and current on a logarithmic scale from 1 mA to 10 A. This leads to a wide range of perceptible charge times and pleasant charge-time contour lines. The prototype is implemented on a single PCB using a cheap PIC micro controller. It is scaled for monitoring a single 18650 lithium cell charged by a small solar panel. The novel contribution of this paper is the use of a cross-needle analog meter with a third scale to measure time remaining to fully charge a Lithium-Ion single cell battery.

**Index Terms**—Lithium-Ion Battery, State of Charge Estimation, Geometric Analysis, Analog Meter, Cross-Needle Meter, Micro-controllers, Standing Wave Ratio meter

## I. INTRODUCTION

Rechargeable batteries are becoming more common in modern electronic devices, ranging from smartphones, laptops, drones and even electric vehicles. One of the widely used rechargeable battery is the 18650 Lithium-Ion single cell. It has proven to be safe, durable, reliable, commonly supplied and affordable. There are many applications for monitoring battery charge, such as mobile apps, mains powered wall chargers or simply a small LCD screen connected to a micro-controller. There may be users who prefer to visualise readings through analog meters rather than to simply view numbers shown on a LCD screen or a 7 segment display. There are many analog SWR meters available and common in the market as well as digital SWR meters.

An analog voltmeter to monitor single Lithium-ion cell had been developed in 2016 which uses a LM285 2.5V band gap reference to provide an expanded scale between 3 V to 4.3 V to suit a voltage range for a Lithium-ion Cell [1].

There are various methods to estimate SoC for Lithium ion batteries these methods are compared in [2]. Coulomb counting requires regular re-calibrations and good current measurements. Impedance spectroscopy is costly and temperature dependent. Kalman filtering can be complicated with algorithms that considers all the aspects [2]. Reference [3] states that to measure Independence only to determine the SoC for a Lithium-Ion cell would be inaccurate at lower SoC. This was also shown by measuring AC impedance analysis in [4]

with errors of 2.6 % at 50 % SoC and 8.6 % at 0 % SoC. Changes in ambient temperatures have small effect on battery EMF. The EMF had an increase of about 42 mV between 5°C to 25°C and a small decrease of about 33 mV between 25°C to 45°C [2].

Ideally a photo-voltaic cell will be used in this project to provide charge current to the battery which can output a current that varies significantly with lighting conditions. A SunPower A300 solar cell was tested in locations with different lighting conditions and was found that the cell outputs about  $20.9mW/cm^2$  outdoors when the sun is approximately at zenith,  $3.03mW/cm^2$  outside the sun on a car dashboard,  $0.42mW/cm^2$  indoors under a lamp and  $0.04mW/cm^2$  next to a window indoors [6]. An expanded current scale is required to monitor this large variation in input current.

One approach to monitor battery charge time is to modify a preexisting cross-needle SWR which the needles cross at a point that indicates standing wave ratio. This idea can be useful for a battery charge monitoring application. One needle displays battery charge by using the analog voltmeter features from [1]. The other displays input charge current. The two needles cross at a point to show a third scale of the time remaining until battery reaches full charge.

The work of this paper is presented as follows. Section II discusses the Lithium-Ion cell tests, Schottky diode tests at different temperature conditions, investigation of different current scales to design an elegant looking meter panel and finally the overall circuit design. Section III describes the firmware of the micro-controller. Section IV discusses the precision of the components used and section V discusses the accuracy of the analog meter.

## II. HARDWARE

A PCB with a 8-bit PIC16F684 micro-controller is mounted on the back of an analog dual SWR meter powered by a single 18650 lithium cell. A dual meter panel displays the battery charge and input current and a third scale to indicate time remaining for the battery to reach full charge. Various hardware components contributed to this project were first tested, measured and studied before the prototype assembly.

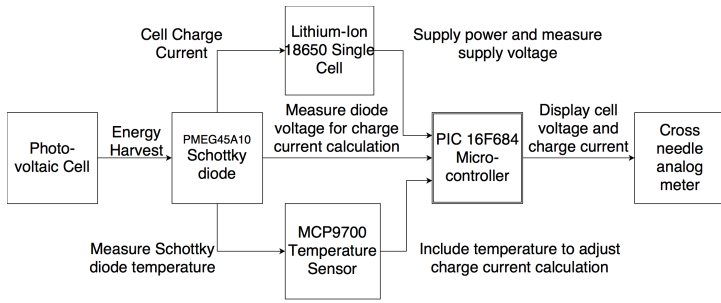


Fig. 1. System diagram of devised hardware

Figure 1 shows the overall function of the devised hardware to monitor battery charge. Energy is harvested using a solar cell to provide charge current for the battery. The Schottky diode acts a shunt for the charge current. Temperature of the diode is monitored to make the device compatible in hot and cold environments. The battery supplies power to the micro-controller. The micro-controller measures supply voltage and calculates charge current in real time. The charge current and battery voltage is displayed onto a cross needle analog meter.

### A. 18650 Lithium-Ion Cell

The charge and discharge tests of the 18650 Lithium-Ion cell were conducted using the Agilent 5270B precision IV analyzer to supply 60 s 0.26 A current pulses while measuring open circuit and closed circuit voltage with the Agilent 34401A digital multi-meter(DMM). Figure 2 and Figure 3 shows the plot of the results at room temperature (23 °C - 25 °C).

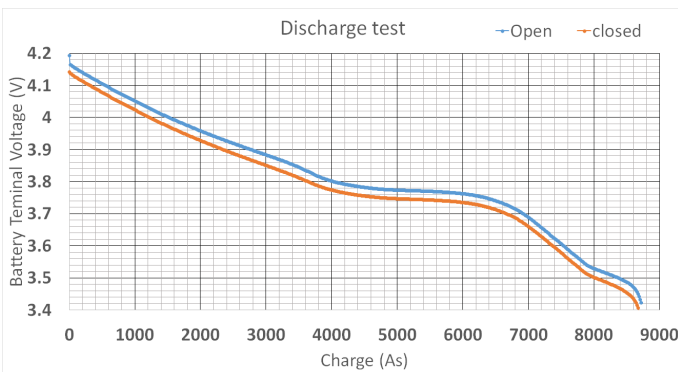


Fig. 2. Comparison of open circuit and closed circuit voltages of a 18650 Lithium-ion cell while discharging

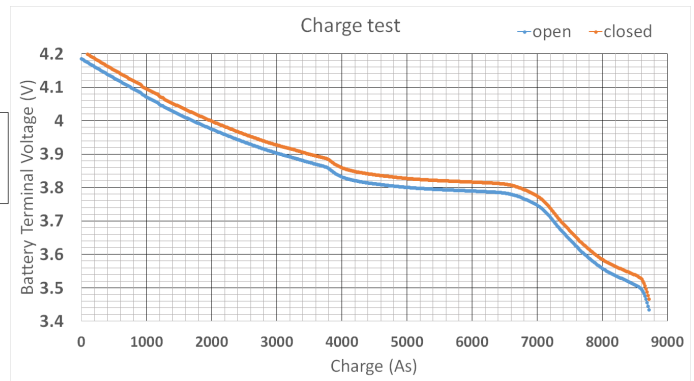


Fig. 3. Comparison of open circuit and closed circuit voltages of a 18650 Lithium-ion cell while charging

Figure 2 and Figure 3 show almost an identical trend with alternated open circuit (blue line) and closed circuit (orange line). Cell voltages at about 3.4 V can be assumed to be flat. It can be seen in the charge test in Figure 3 that cell reaches full capacity between voltages of 4.18 V to 4.2 V. The internal impedance ranged between 176 mΩ to about 103 mΩ for the discharge test and 122 mΩ to about 90 mΩ for the discharge test.

It can be seen in both plots that voltage falls at a steep inline between 0 As to 4000-4500 As then falls steadily between 4500 As to 6500 As then rapidly declines below 6600-7000 As.

### B. PMEG45A10 Schottky Diode

The Voltage across the Schottky diode was measured with the 34401A DMM while placed into the incubator to change the ambient temperature. The current was set from 0.5 mA to 1 A with 50 steps and supplied by the 5270B IV analyzer.

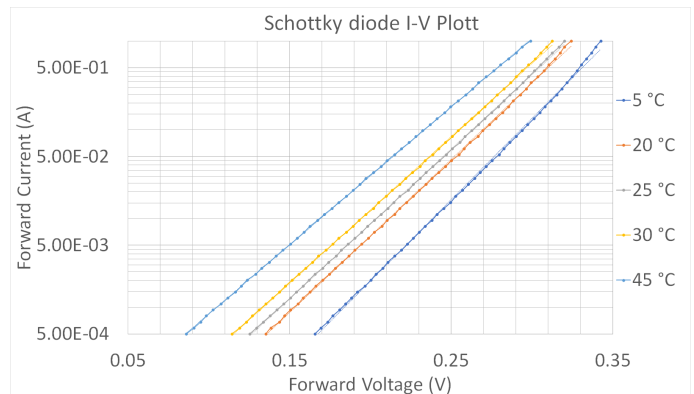


Fig. 4. Schottky diode IV characteristics at different ambient temperatures

The plots in Figure 4 are in different colours to indicate readings at a different ambient temperatures: 45 °C in light blue, 30 °C in yellow, 25 °C in gray, 20 °C in orange and 5 °C in blue. The Schottky diode current is displayed in a logarithmic scale to form a linear graph and the Schottky diode voltage on the x axis remains in a linear scale. Trend lines were

used to approximate saturation current, thermal voltage and n factor. These values were used in the firmware for calculations.

### C. Meter Panel Design

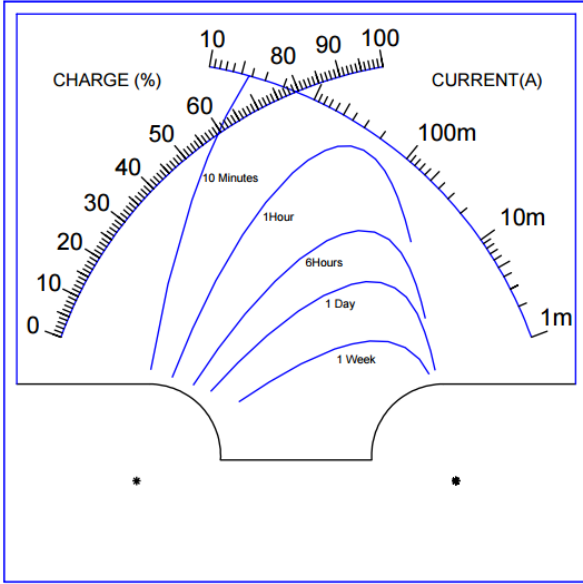


Fig. 5. Custom print of the face of the SWR panel meter.

The custom panel face in Figure 5 was drawn by measuring the dimensions of the SWR meter then using Solidworks 2016 SP0 and a macro written in C# to draw the contour lines. The two points at the bottom indicate the axis of rotation for each needle. The current has a logarithmic scale and the contour lines in the middle indicate the time left for the battery to charge. The numbers 80 % and 1 A are not printed as it would make the numbers clutter around where the scales cross and hence more difficult to read the meter.

The contour lines were drawn using geometric analysis. The left and right meter needles can be represented by Cartesian coordinates using the following equations:

$$y = x \tan \theta_L \quad (1)$$

$$y = -x \tan \theta_R + 38 \tan \theta_R \quad (2)$$

Solving for (1) and (2) gives the points where the two needles intersect. Angles  $\theta_L$  and  $\theta_R$  are found using the following equations:

$$\theta_L = 6.514 \ln(I_{ch}) + 65 \quad (3)$$

$$\theta_R = 160 - 0.6q \quad (4)$$

Charge  $q$  in (4) is the battery charge (%) and charge current in (3)  $I_{ch}$  can be found using the following formula:

$$I_{ch} = 3600t(2.5 - 2.5q/100) \quad (5)$$

In (5), with given time,  $t$  and an array of battery charges from 0 % to 100 % and an array of intersection coordinates can be

generated. By joining these points a contour line can be drawn for the particular given time.

### D. Circuit Design

The circuit is designed to mount directly onto the back of the meter. Dimensions of the back of the meter were measured with vernier calipers then a custom foot print with larger pads were created to provide enough strength to prevent the pads from coming off.

The analog SZ-70 SWR meter was tested using a bench top power supply and requires 100  $\mu$ A for a full scale deflection(FSD) and each meter terminal has a total resistance of 1.54  $K\Omega$  measured with a DMM. The measured values agree with the specifications provided by the manufacturer.

In Figure 7, input supply current is drawn through a low forward voltage Schottky diode to charge the battery. The forward voltage across the Schottky diode increases logarithmically with current. The voltage is measured across the anode and cathode of the Schottky diode is then amplified by the low power opamp for the micro-controller to calculate the charge current. The temperature is constantly monitored by a sensor which is placed close to the Schottky diode as the IV characteristics of the Schottky diode varies significantly with ambient temperature. The temperature sensor outputs a set voltage regardless of varying supply voltages. The four terminals of the dual analog meter connects to the appropriate Vmeter+, Vmeter-, Imeter+ and Imeter- outputs. The battery terminals are connected to a protection circuit that prevents overcharging.

The PCB design was done using Eagle CAD version 7.70 The top layer copper is in red, bottom layer in blue, pads are in green and silkscreen are in white.

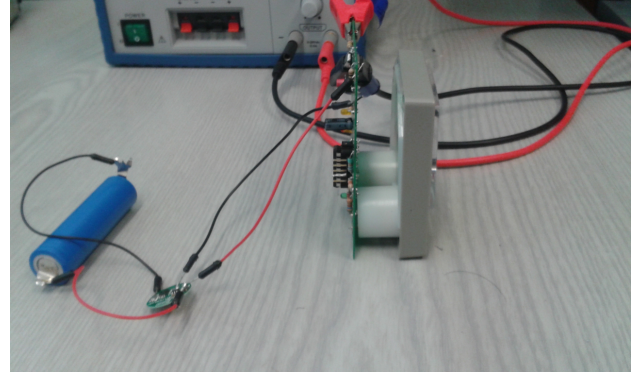


Fig. 6. Photograph of the PCB mounted onto the back of the panel with the 18650 cell and bench top power supply connected.

In Figure 6 it can be seen that the Pads perfectly align to the back of the meter therefore can be easily be mounted.

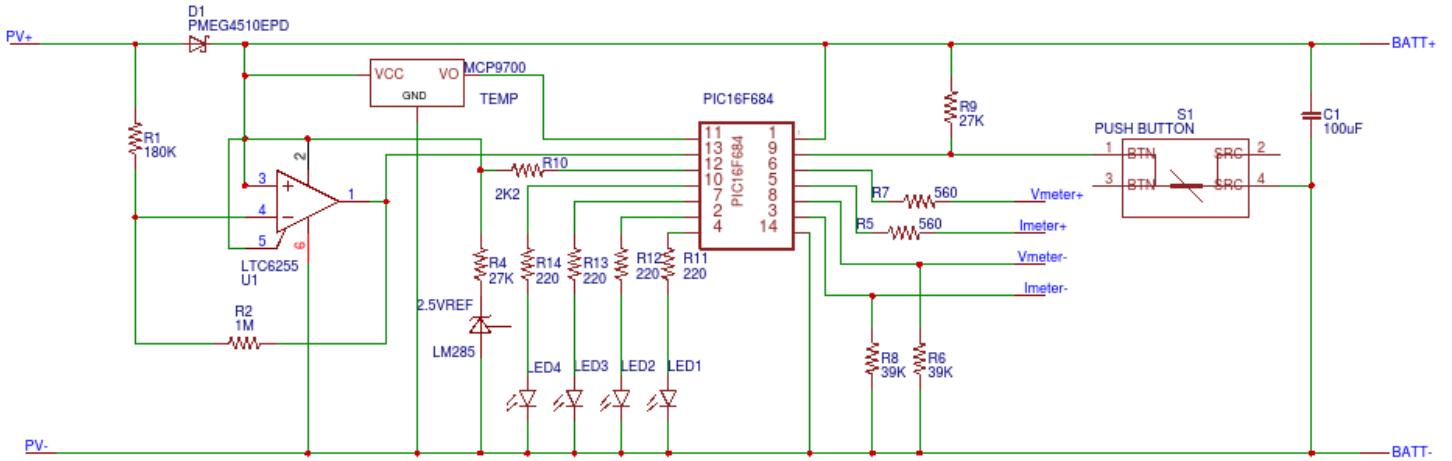


Fig. 7. Circuit diagram of the Cross-Needle meter.

### III. FIRMWARE

The PIC16F684 has the following functions:

- Measures 2.5 V band gap voltages as reference.
- Measures and converts temperature sensor voltage to degrees Celsius to obtain board temperature.
- Calculates the saturation current of the Schottky diode from ambient temperature.
- Estimates input battery charge current from Schottky diode voltage.
- Uses the 8-bit Timer 0 for software PWM to drive the voltage analog meter and the built in 8-bit PWM drives the current analog meter.
- Adjusts PWM for varying supply voltages.
- Green LED turns on to indicate battery is fully charged.
- Red LED turns on to indicate dead battery.

The log of charge current can be a function of temperature using the linearised formula:

$$\ln(I_d) = \ln(I_s) + V_d/V_{TH} \quad (6)$$

$I_s$  in is the saturation current calculated by formularising the y intercepts in the Schottky diode plot. The Thermal Voltage,  $V_{TH}$  determines the gradient in (6). This can also be calculated as a function of temperature:

$$V_{TH} = nKT/q \quad (7)$$

K is the Boltzman constant and q is the electrical charge of an electron. The ideality factor, n in (7) is assumed to be 1. Changes in n with temperature is neglected as it is found by analysing the Schottky diode I-V characteristic plot in Figure 4 that changes are very small ranging from -1.2 % to +1.9 %.

67.7 % program and 48.4 % of the data memory was used. Compiled using Hi-Tech C standard version 9.8

### IV. PRECISION

The temperature sensor was tested inside a Contherm polar 1000 incubator with adjustable temperature. Output voltages were 0.4 V at 0 °C and 0.84 V at 25 °C as opposed to the 0.5 V at 0 °C and 0.75 V at 25 °C suggested by the data sheet. The LM285 was tested by varying the supply voltage with a bench top power supply while measuring the output voltage with a DMM. The reference voltage stayed constant at 2.500 V.

### V. RESULTS

The voltmeter accuracy is shown in Figure 8 compares the actual DMM reading to the voltmeter reading:

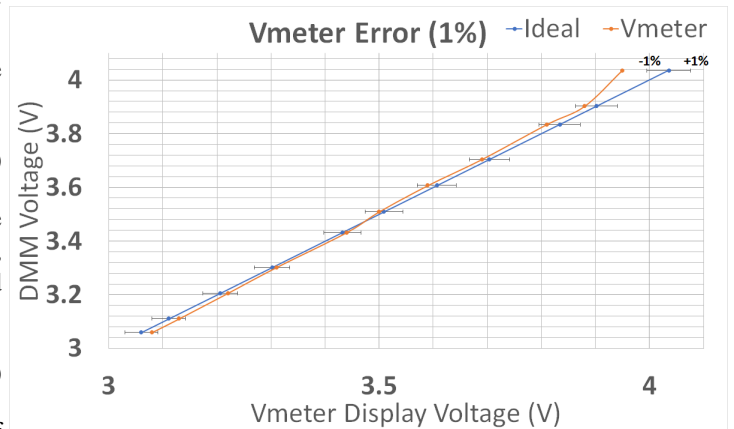


Fig. 8. Plot of the voltage meter accuracy

In Figure 8, the circuit was tested by connecting a bench top power supply to the battery input terminals while the voltage was measured with a DMM. The blue plot line shows the ideal reading with 0 % error and the orange plot line is the readings

displayed by the voltmeter which are within the boundaries of the black 1 % error bars.

Current meter testing was done using a bench top supply and supply current was increased logarithmically from 1 mA to 1 A. The current meter accuracy was compared to actual DMM readings. In Figure 9 the current meter was tested at different ambient temperatures. The blue line represents the ideal readings and the orange line represents the readings observed from the Analog Cross-Needle meter. It can be seen that it performs well at lower temperatures and accuracy begins to fall at higher temperatures.

## VI. CONCLUSION

This project concludes that using the cross-needle analog meter is indeed useful for quick referencing and battery charge monitoring with a wide range of input supply current. Hopefully this novel tool for gauging the time required to charge a battery will find a plethora of applications in the future.

## ACKNOWLEDGMENT

Gratitude goes towards Benson Chang for ordering and providing the hardware, Jonathan Scott for providing and suggesting ideas and assistance with all facets of this project.

## REFERENCES

- [1] Jonathan Scott, "Accurate Low-Cost Expanded-Scale Analog Voltmeter with Novel Charge/Discharge Indication for Monitoring Single Lithium-Ion Cells", University of Waikato Research Commons, 2016, hdl:10289/10003.
- [2] Pop, V., Bergveld, H.J., Danilov, D., Regtien, P.P.L., Notten, P.H.L., "Battery Management Systems - Accurate State-of-Charge Indication for Battery-Powered Applications", Philips Research Book Series Volume 9, 2008. pp38-69
- [3] Martin Coleman, Chi Kwan Lee, Chunbo Zhu, and William Gerard Hurley, State-of-Charge Determination From EMF Voltage Estimation: Using Impedance, Terminal Voltage, and Current for Lead-Acid and Lithium-Ion Batteries, IEEE Transactions on industrial electronics, VOL. 54, NO. 5, October 2007.
- [4] Hung-Cheng Chen, Shuo-Rong Chou, Hong-Chou Chen, Shing-Lih Wu, and Liang-Rui Chen, Fast Estimation of State of Charge for Lithium-ion Battery, IEEE International Symposium on Computer, Consumer and Control, 2014
- [5] F. Baronti, G. Fantechi, L. Fanucci, E. Leonardi, R. Roncella, R. Saletti, S. Saponara, "StateofCharge Estimation Enhancing of Lithium batteries through a TemperatureDependent Cell Model", IEEE Applied Electronics (AE) 2011 International Conference, 7-8 Sept 2011, ISSN:1803-7232
- [6] Gabriela E. Bunea, Karen E. Wilson, Yevgeny Meydbray, Matthew P. Campbell and Denis M. De Ceuster SunPower Corporation, "LOW LIGHT PERFORMANCE OF MONO-CRYSTALLINE SILICON SOLAR CELLS", IEEE Conference, 7-12 May 2006, DOI: 10.1109/WCPEC.2006.279655

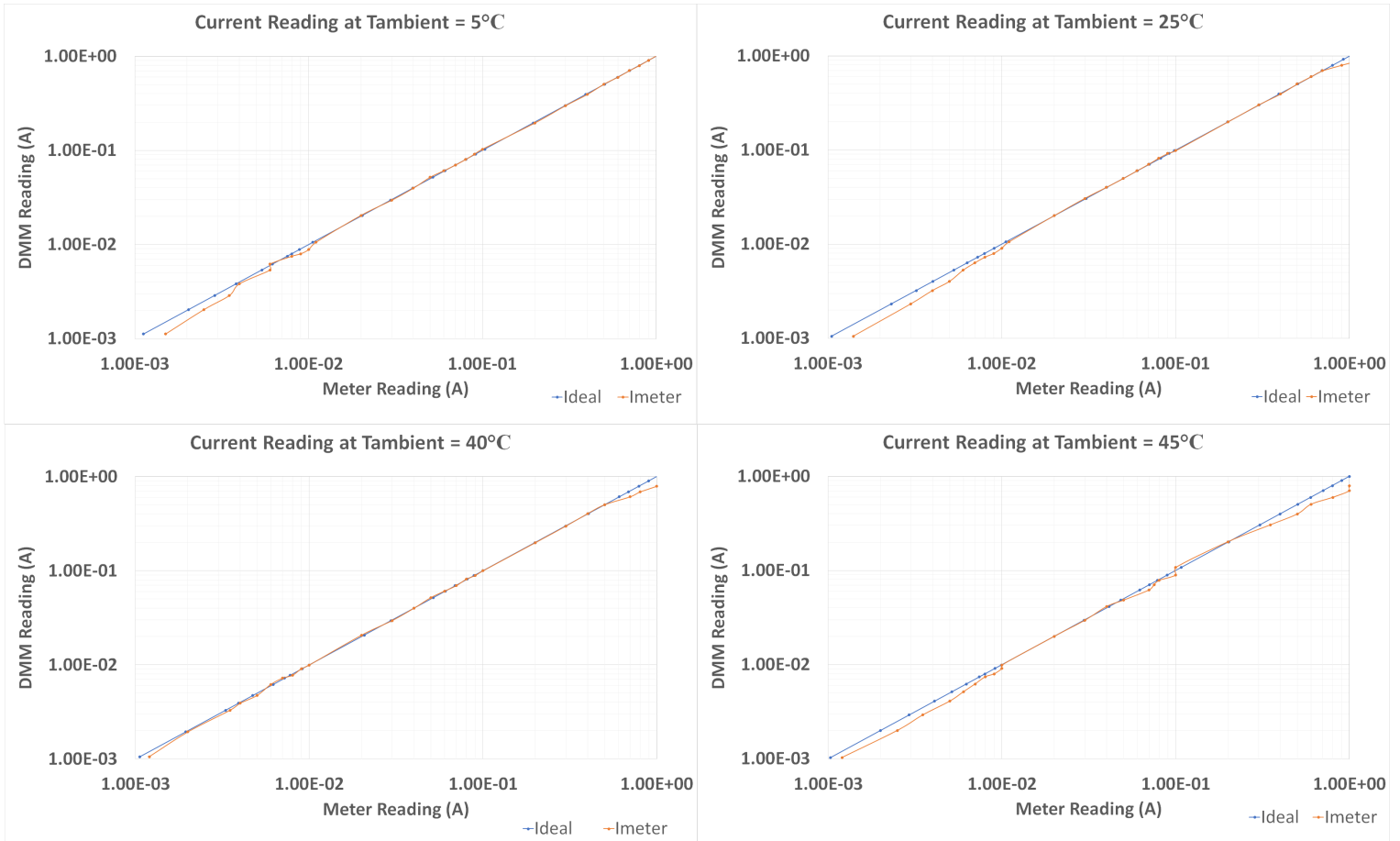


Fig. 9. Plot of the current meter accuracy at different temperatures