Measurements of DC Internal Resistance and its Variations with State of Charge and Cycle Age of a Sealed Lead Acid Battery

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Outline

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- Need for Innovations in Lead Battery Management
- Battery Management System
- State-of-Charge (SOC)/State-of-Health (SOH) Battery Parameters
- Experimental Setup
- Novel Method for Determining Internal Resistance
- Results
- Conclusions

Need for Innovations in Battery Management

- Solar Electric System in Burundi

Battery Management System Block Diagram

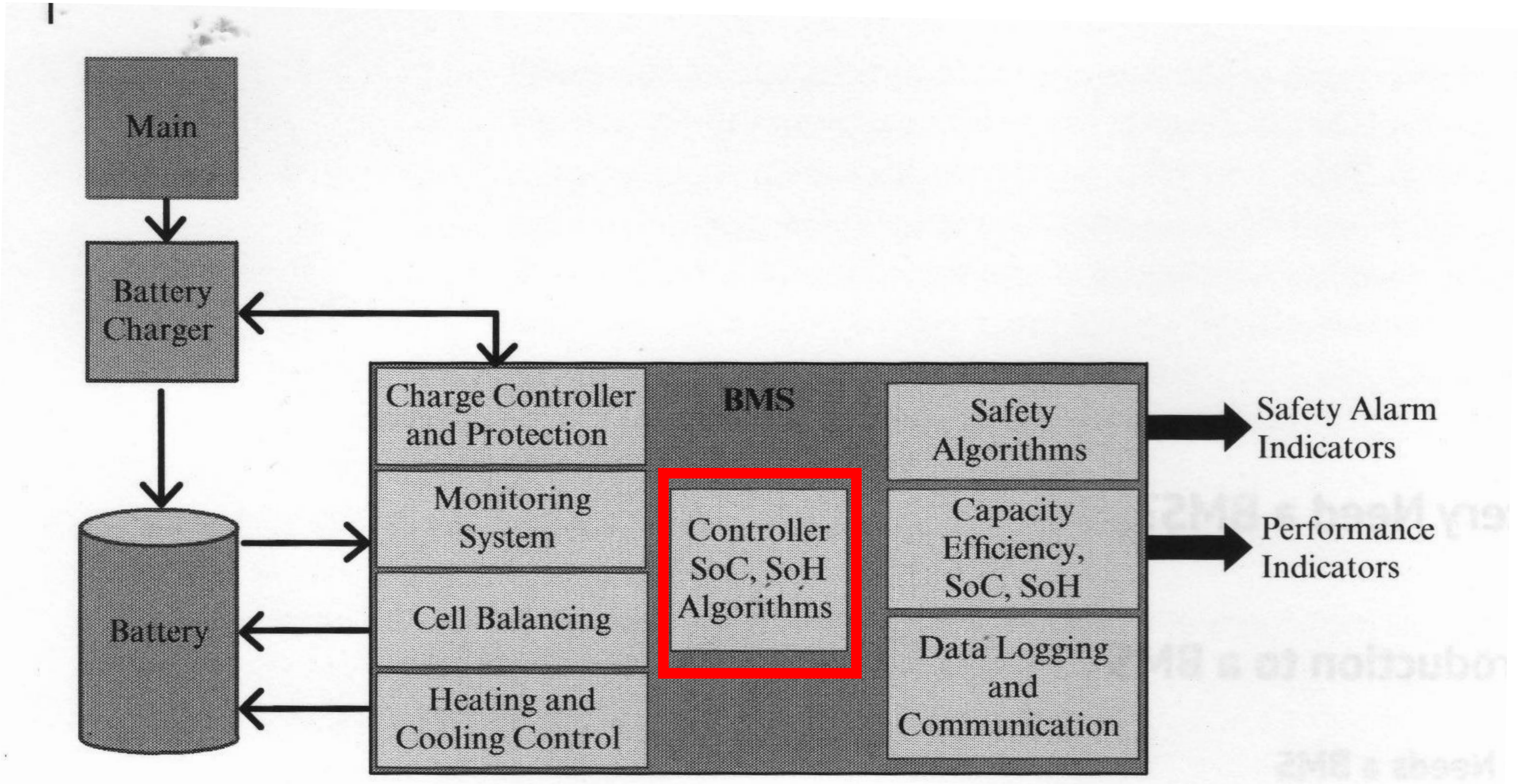


Figure 1.1 Block diagram of a battery management system.

<u>Source</u>: X.Tan, A. Vezzini, Y. Fan, N. Khare Y. Xou and L. Wei, "*Battery Management System and its Applications*", Wiley 2023

State of (SOC) and State of Health (SOH) for Batteries

Ensuring reliable and efficient operation of batteries

Estimate SOCand SOH of batteries

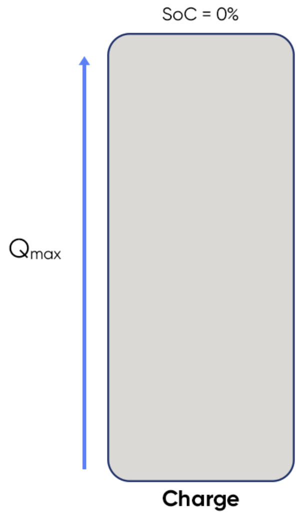
SOC: gives insights into its present energy status. Facilitates to know the available energy, enabling planning the usage of the battery accordingly.

Avoids over-charge and over-discharge scenarios.

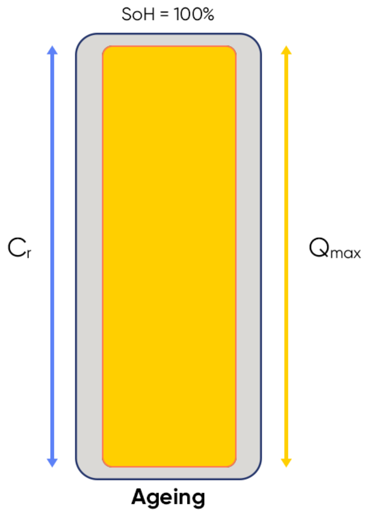
SOH: assessment of its overall condition and the prediction of its remaining useful life.

Replacement or maintenance before failure.

$$\mathrm{SoC}/\% = 100\frac{(Q_0 + Q)}{Q_{\max}}$$



$$\mathrm{SoH}/\% = 100\frac{Q_{\max}}{C_r}$$



Possible Battery Parameters

Measurable battery parameters, and their variations, which can indicate SoC/SoH estimates of the battery at its available level of charge/discharge were identified as:

- Terminal voltage under load discharge ($V_{underload} = V_L$);
- Variation of load voltage (V_L) with time (h), during a continuous discharge at constant current (CC);
- Stabilized load voltage (open circuit) ($V_{L.stable}$), after a discharge to V_L for different charge levels;
- Cycle/Calendar age of the battery – cycles (n), days (d) or years (y);
- DC Internal Resistance of the battery - (DCIR);
- Battery Internal Impedance (Z_{int});
- Battery Capacity C_n (Ah), where n = cycle age of the battery; and
- Capacity loss during an idle period - Rate of Self-Discharge (SD).

Battery Parameters Selected for Measurement

The selected parameters and their variations, which were considered relevant to characterize the battery for its database, for the SoC/SoH estimation technique are listed below:

1. V_L vs. % SoC (during continuous discharge at C/10 rate between open-circuit voltage (OCV) to end of discharge voltage (EODV)) for batteries of different cycle ages, n.
2. $V_{L.stable}$ vs. V_L (during discharge at C/10 rate between OCV to EODV) of batteries for different cycle ages, n.
3. DCIR vs % SoC
4. DC internal resistance DCIR vs cycle age, n (cycles),

where,

V_L = Battery voltage at any point ‘x,’ during a continuous C/10 CC discharge

$V_{L.stable}$ = Stabilized battery voltage corresponding to the V_L at the point ‘x,’ during the CC step discharge (1 hour after stopping discharge at the point ‘x’), and

DCIR = Battery internal DC Resistance and

n = One of the nine cycle-age stages of the rated battery life.

Experimental Setup

Equipment used:

- Programmable digital DC Power Supply:
  Chroma, 63205A-150-500

- DC electronic load, Chroma

- Charge-discharge software

- 6 Digit Multimeter – Agilent, 34401, 6 ½ Digit Multimeter

- Five new sealed lead acid batteries (Enersys, 12 V, 200Ah)

Battery Cycle Aging

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- Repetitive charge/discharge (cycling) to obtain nine cycle-age stages of the battery life.

- Cycling profiles - designed for Constant Current (CC) discharging at 40A (C/5) rate, and manufacturer-recommended (Constant Voltage (CV) + float) charging approach.

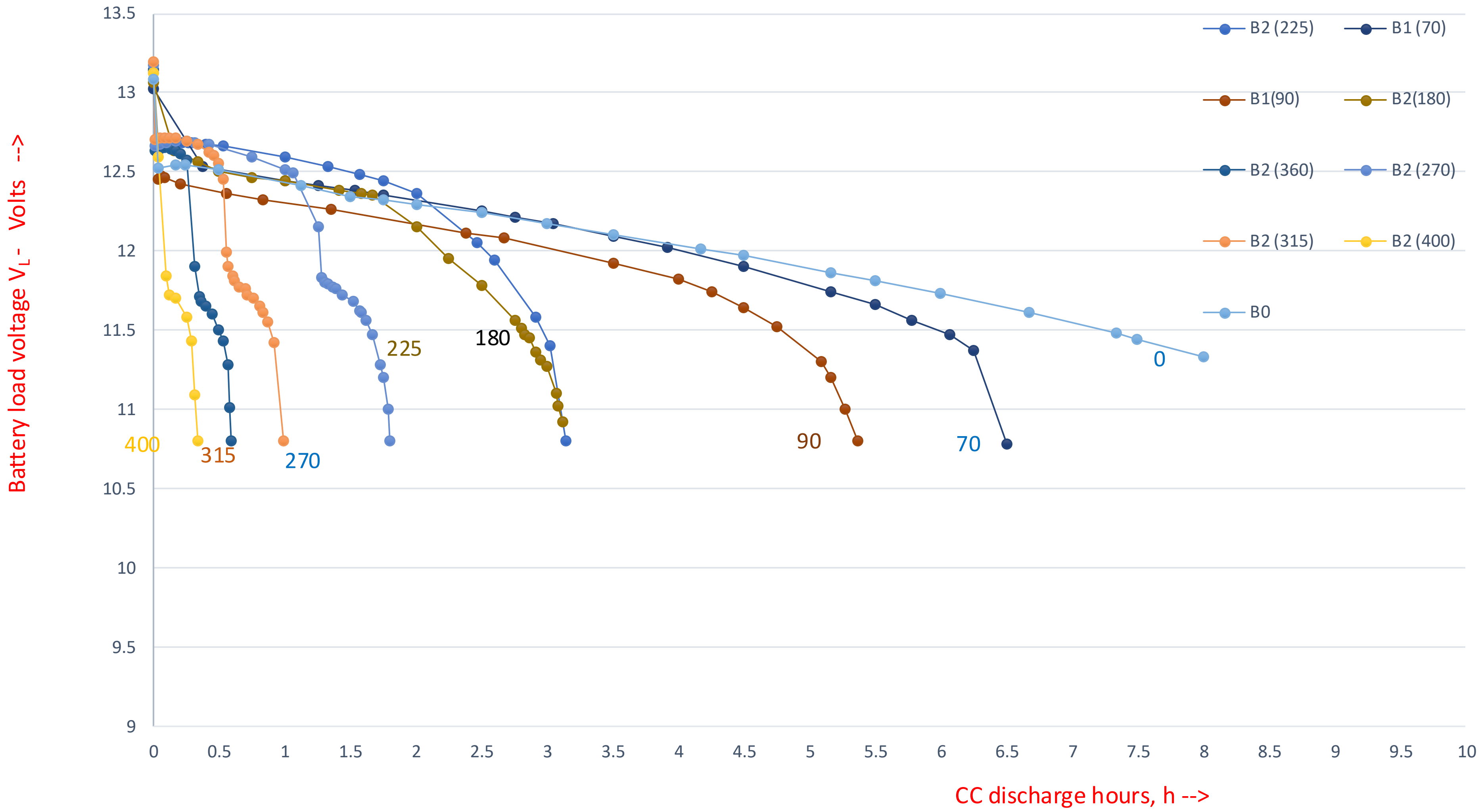
An exemplary cycling profile:

a) Charge: 20% SoC to better than 95% SoC – CV @ 14.8 V, I_{cmax}: 50A ~ 2 hrs., followed by 3 hrs of float charge at 13.7V. Total: ~ 5 hrs (for a new battery)
b) Discharge: CC @ C/5 (40A/hr) for 0 to 80% DoD ≤ 4 hrs (for a new battery)

Total Number of cycles:

The new batteries were cycled through nine stages of battery cycle-ages (0, 70, 90, 180, 225, 270, 315, 360, and 400 cycles)

Battery Discharge Curves as a function of Cycle Number



Novel Virtual Open Circuit Voltage Method to measure DCIR

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- Idea: 2-I method → VOCV concept (CRs → CC)
- *Procedure:*
- Connect fully charged battery to DC electronic load
  → CC and its measurement.
- Start C/10 CC discharge (I_d), till V_L starts falling after its initial rise (this time varied from 3-4 to ~40 minutes, depending on battery health).
- Stop I_d discharge and note V_L at this instant.
- The stabilized virtual open circuit voltage (VOCV) (=$V_{L.stable}$), after 1 hr. of recovery after stopping the discharge is then measured.

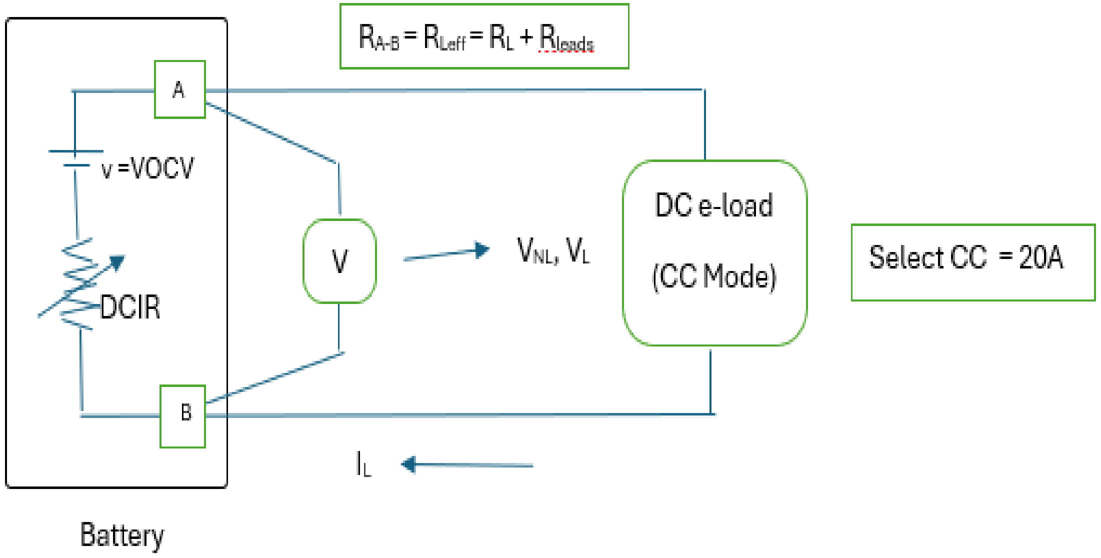

Fig 3.7 DC Internal Resistance (DCIR) Measurement - New VOCV Method

Novel Virtual Open Circuit Voltage Method to measure DCIR (cont'd)

- R_{int} for a fully charged battery using the above load current-interruption method:

$$R_{int} = (VOCV - V_L) / I_d$$

where,

VOCV = Virtual OCV of the battery, 1 hr. of recovery after stopping discharge at V_L

~ *OCV (when discharge is from full charge level of the battery)*

V_L = Battery load voltage (=V_L) when the load current I_d is interrupted (after V_L stopped rising during I_d discharge and has started to fall).

Observations/Comments on this New Method

A few observations / Comments:

- Since R_{int} varies with the battery discharge current, its SoC, and its remaining capacity, its earlier measurement methods, accompany inaccuracies and procedural constraints.
- The VOCV method resolves these issues.
- We believe that it adds to the knowledge base in the field of R_{int} measurement.
- Advantages over the other approaches:

  a) VOCV method offers a novel practical method for R_{int} measurement of any given lead-acid battery, at the desired discharge current and its charge/discharge level.

  b) It is a short duration (about 1½ hr.) measurement method.

  c) The observations are steady and repeatable.

DCIR vs. %SOC for three different cycle numbers

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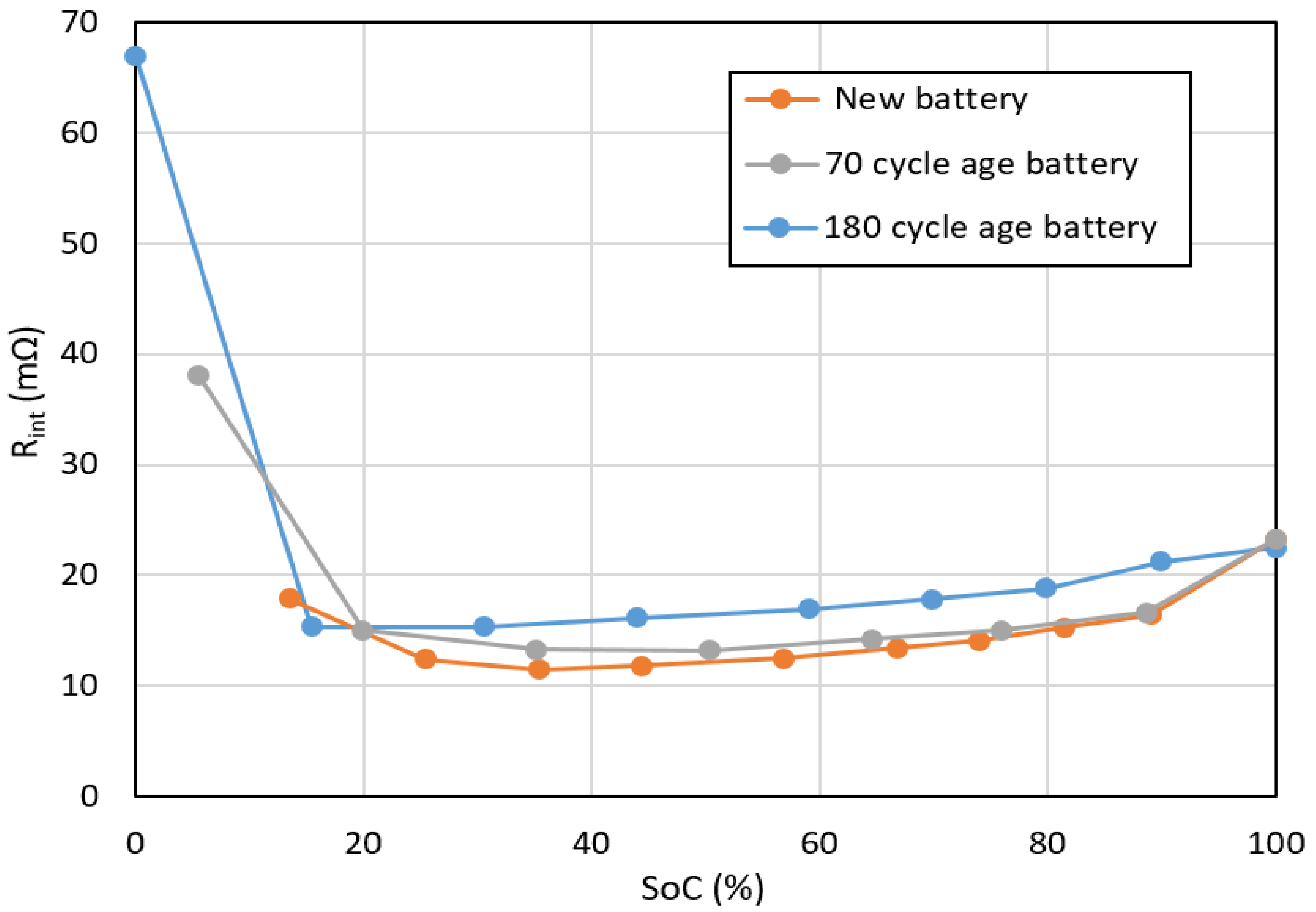
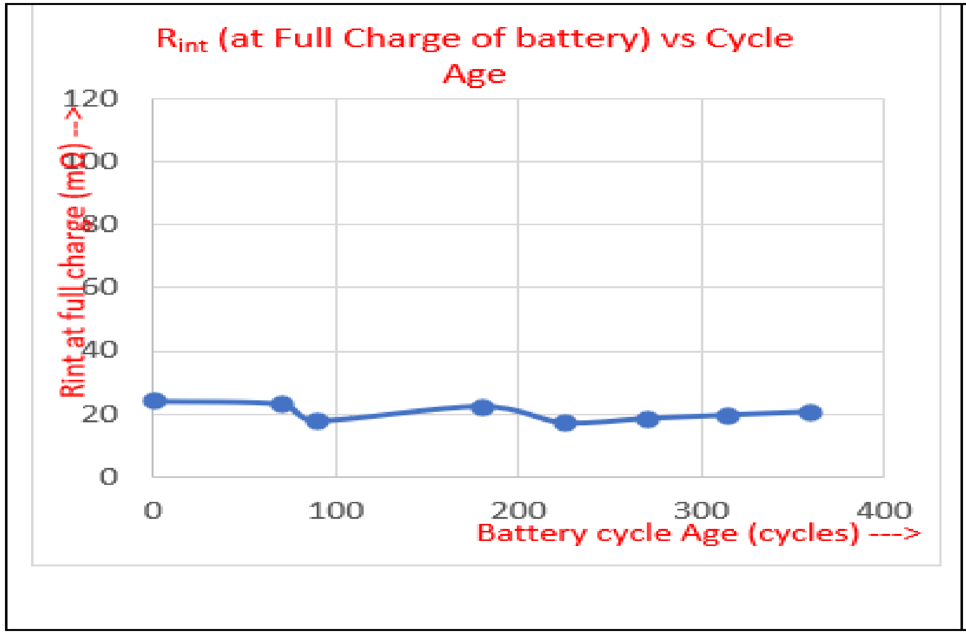
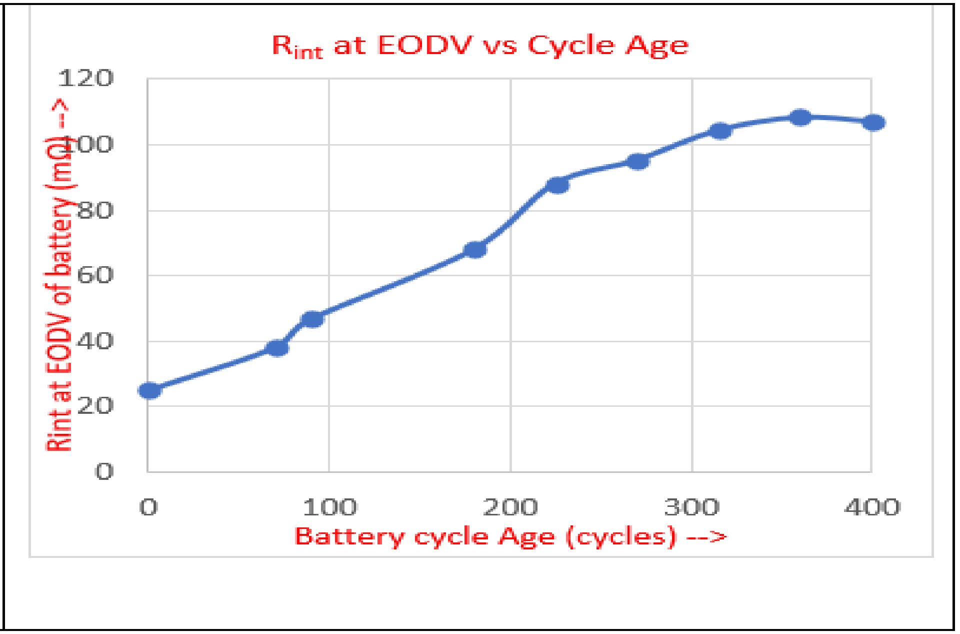


Internal Resistance of Battery vs. Cycle Number

- Nine R_{int} values → R_{int} vs %SoC plots for battery's nine cycle-life stages at 100% SoC and at EODV levels
- Data was compiled for R_{int} values at full charge and R_{int} values at EODV, for each cycle life stage of battery R_{int} vs Cycle age and R_{int} vs Load current) → Plots of R_{int} at full charge and R_{int} at EODV;





- Analysis of R_{int} at EODV indicates a significant increase in R_{int} values with an increase in cycle age!!

Conclusions

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- Charge discharge cycling of 12V, 200Ah sealed lead acid batteries through 9 stages of their rated cycle life of 400 cycles – 0, 70, 90, 180, 225, 270, 315, 360, and 400 cycles were completed.
- A novel VOCV-based DC load method has been developed for simple accurate and reliable, DCIR measurements of a Sealed Lead Acid Battery of any age, during a given discharge current and at any of its charge levels. "DCIR at EODV" measurements have been successfully used for SoC/SoH estimation and accuracy improvement.
- This innovative measurement-based approach, for %SoC/%SoH estimation has been identified, tested, and validated. The new technique is a simple, valuable, and experimentally validated technique for sealed lead acid batteries.
- %SoC and %SoH estimates of a test battery made using the battery database derived from a different battery validated the newly developed technique.

Acknowledgements

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Thank You for Your Attention!

Questions?