EC-003 · MODULE 3 OF 22

Voltage, Current, and Resistance in DC Systems

What each one is, where each one shows up, and how each one is measured in CP work.

EXTERNAL CORROSION TRACK · FOUNDATION TIER · ELECTRICAL BASICS FOR CP · ~30 MINUTES

BY THE END OF THIS MODULE

You'll be able to —

- Distinguish **voltage**, **current**, and **resistance** by role and by measurement setup.
- Identify what a **structure-to-soil potential** reading represents and apply the **−0.85 V Cu/$CuSO_4$ criterion**.
- Name the **four resistances** that show up in a CP system and how each is measured.
- Recognize the **four canonical CP measurements** (S-to-S V, rectifier V/I, bond shunt I, soil resistivity).
- Combine multiple readings into a **single system-health diagnosis**, applying Ohm's Law from EC-002 to back out total circuit resistance.

OUT AT A TEST STATION

You kneel down and open the box.

Pipe header lead in your left hand. **$Cu/CuSO_4$ half-cell** in your right — copper rod, saturated copper sulfate, porous plug. Multimeter set to **V DC**. You press the half-cell into moist soil next to the pipe.

Black lead from the meter to the half-cell. Red lead to the pipe header bond. Display settles at **−0.94 V**.

> **The question.** Is the pipe protected? — Yes. But why does that answer come from a *voltage* reading? And what makes this voltage different from current or resistance?

THE READING

What is the meter actually telling you?

−0.94 V

DMM · V DC · VS $CU/CUSO_4$ REFERENCE

A voltage. Specifically: the difference in electrical potential between the pipe and the soil at this location, with the half-cell providing the soil reference. **Voltage is always between two points.** The half-cell is the second point.

It's a voltage. Voltage requires a reference. The reference is what makes the reading mean something.

WHAT WE'LL COVER

Three quantities, three jobs — and the readings that name each one.

01
Voltage
Pressure between two points · Cu/$CuSO_4$ reference · −0.85 V criterion

02
Current
Flow that does the work · rectifier output · bond shunts · current density

03
Resistance
Opposition · the four R's of CP · how each is measured

04
Four CP measurements
S-to-S V · rectifier V/I · bond shunt · soil resistivity

05
Three readings, one diagnosis
Synthesis — what the trio tells you about system health

SECTION 1 OF 5 · SLIDES 7–13

Voltage — pressure, with a reference.

WHAT VOLTAGE IS

Always between two points. Never at one spot.

Voltage is electrical pressure — the driving force that pushes current through a circuit. The unit is the **volt (V)**. The variable is **V** (sometimes **E** in older CP manuals).

> **The "between" property.** A voltmeter has two leads for a reason. It reads the difference in electrical potential between wherever you put the red lead and wherever you put the black lead. Move either lead and the reading changes. There is no such thing as "the voltage at this spot."

For most CP voltages, both points are obvious — rectifier (+) and (−), or two ends of a cable. Structure-to-soil potential is the one that needs a reference electrode to make the soil side a defined point.

CP VOLTAGES — WHERE THEY LIVE

Four kinds of voltage you'll meet in the field.

Rectifier output voltage

The source pressure the impressed-current rectifier delivers. Read between (+) and (−) terminals. Typically 12–50 V DC.

Structure-to-soil potential

The canonical CP voltage. Pipe vs. soil, referenced through a Cu/$CuSO_4$ half-cell. The −0.85 V criterion is judged here.

Junction-box voltage

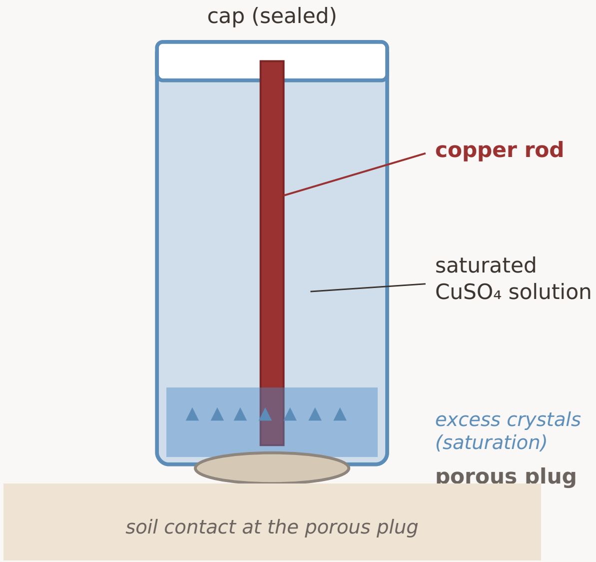
Source voltage minus the cable IR drop. Read at the (+) bus inside the junction box. Tells you what's left to push across the anode-to-soil interface.

IR drop voltage (V across a resistor)

Cable IR drop, shunt mV, anode lead drop. Each one measures the voltage consumed across a known resistance — and ties to current via Ohm's Law.

THE $CU/CUSO_4$ HALF-CELL — ANATOMY

A defined contact with the soil.



Three components inside a small portable cylinder:

- **Copper rod** — the connection to your meter lead. Runs down through the cell into the saturated solution.
- **Saturated $CuSO_4$ solution** — copper sulfate in water, with excess crystals at the bottom to keep it saturated regardless of temperature or evaporation.
- **Porous plug** — at the bottom of the cell. Lets the solution make ionic contact with whatever the cell is touching, while keeping the inside of the cell sealed.

Press the plug into moist soil and the cell becomes a defined, repeatable electrical contact at one specific point.

WHY $CU/CUSO_4$

The practical default for buried-pipeline CP work.

Stable

The chemistry inside the cell sets a fixed reference potential — within a few millivolts, regardless of who's holding it.

Repeatable

Two CP techs walking the same line on the same day with the same kind of half-cell read the same potential at the same spot.

Well-correlated

Decades of accumulated CP criteria (the −0.85 V floor, the 100 mV polarization criterion) are all defined against $Cu/CuSO_4$.

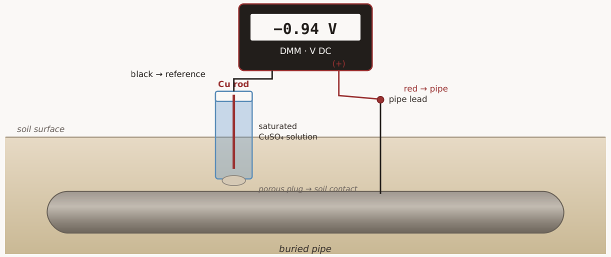
Easy to maintain

Field kit: solid copper rod, copper sulfate crystals, distilled water. Refresh as needed. Inexpensive, durable, no special handling.

Other reference electrodes exist — silver/silver-chloride for seawater, zinc for some long-term applications — but each has a different reference potential and the CP criteria need adjustment. $Cu/CuSO_4$ is the buried-steel standard. (Other electrodes + conversions: later module.)

STRUCTURE-TO-SOIL POTENTIAL — THE MEASUREMENT

The canonical CP voltage reading.



Half-cell in soil + meter lead to pipe = a defined two-point voltage measurement.

THE −850 MV CRITERION

The standard floor for protected steel.

A structure-to-soil potential of **−0.85 V or more negative** against $Cu/CuSO_4$ is evidence of cathodic protection on a buried steel structure. The negative sign is part of the criterion.

−0.55 V

No CP applied

Typical of a pipe sitting in moist soil with no cathodic protection. Reads between roughly −0.40 V and −0.65 V. Does not meet the −0.85 V criterion.

−0.94 V

Meets criterion

The hook reading. More negative than −0.85 V, so cathodic protection is in evidence at this location.

−1.20 V

Impressed current driving hard

Strongly negative readings like this typically mean an impressed-current system is pushing significant current at this point. Whether the structure is actually over-polarized can't be determined from the on-potential alone — that needs IR-drop correction (covered later in this rung).

What's NOT in this module: IR-drop correction, instant-off potentials, polarized vs. on-potential criteria, and the 100 mV polarization criterion. All later in this rung.

SECTION 2 OF 5 · SLIDES 14–18

Current — the flow that does the actual job.

WHAT CURRENT IS

Charge in motion. The work doing.

Current is the rate of electrical charge flow through a circuit. The unit is the **ampere (A)**. The variable is **I**.

If voltage is the pressure pushing on the system, current is the water actually moving through the pipe. **In CP work, current is what does the protective electrochemical work** at the structure surface. No current, no protection.

> *The voltage criterion (−0.85 V) is how we confirm enough current is flowing. Voltage tells the story; current writes it.*

CP CURRENTS — WHERE THEY SHOW UP

Three places. Three different stories about the same circuit.

→

PLACE 1

Rectifier output

What the impressed-current power supply puts into the system. Read with your multimeter on volts DC at the output terminals, plus a multimeter on millivolts DC across the rectifier shunt. Typical: 5–50 A.

⇄

PLACE 2

Bond shunt at a test station

Galvanic anode bond, foreign-line bond, test connection. Read in mV across a calibrated shunt → converted to amps via Ohm's Law (EC-002). Typical: a few mA to a few A.

↓

PLACE 3

Structure surface

What's actually happening at the metal-soil interface. Measured indirectly via current density coupons or polarization techniques.

The three are connected. The rectifier sources the current. The cable + groundbed delivers it. The interface is where it does the work. A failure at any one point shows up as a different reading at a different place — which is why a CP tech walks all three.

READING CURRENT VIA A SHUNT

A measurement EC-002 walked end to end.

A shunt is a calibrated low-Ω resistor in series with the current you want to measure. You read the millivolts across it and apply Ohm's Law to get amps.

$$I = V_{\text{across shunt}} \div R_{\text{shunt}}$$

The CP-relevant cases: rectifier output shunt (typically 0.001 Ω or 0.01 Ω, labeled mV-at-A) and test-station bond shunts (typically 0.1 Ω or 0.01 Ω). Same Ohm's Law, different scales. Full mechanics of the calculation are in EC-002.

Whenever a CP tech reads "current" with a regular multimeter, they're almost always reading a voltage drop across a known shunt — and converting via Ohm's Law.

CURRENT DENSITY — NAMED, NOT TAUGHT

Why total amps isn't the whole story.

Current density is current per unit area of structure surface — typically expressed as mA/ft^2 or $\mu A/cm^2$ of bare steel.

> **Why it matters:** a 30-amp system on a 50-mile pipeline delivers a different current density than the same 30 amps on a 5-mile pipeline. The CP criterion isn't really about total amps — it's about whether enough current per unit of bare-steel surface reaches the structure to drive the cathodic reaction.

Coating quality, structure geometry, and groundbed placement all show up as differences in delivered current density, even if the rectifier amperage stays the same.

FORWARD POINTER

Current density values + measurement

Specific design current densities by structure type (bare steel, coated, well-coated), current density coupons, and polarization technique are covered in a later EC module.

SECTION 3 OF 5 · SLIDES 19–23

Resistance — opposition, sets the budget.

WHAT RESISTANCE IS

Opposition to flow. Sets the current budget.

Resistance is opposition to current flow. The unit is the **ohm (Ω)**. The variable is **R**.

The "budget" framing matters in CP. The rectifier can only push so much voltage. **I = V ÷ R** says total resistance sets the ceiling on how much current any given voltage can deliver. Every resistance in the circuit eats some of the budget.

$$I_{max} = V_{source,max} \div R_{total}$$

When R climbs over time — anodes consuming, soil drying, connections oxidizing — current available to protect the structure drops at the same source voltage. That's why we track total R against design.

THE FOUR R'S OF CP

Resistance lives in four places. Each one matters.

Anode-to-soil resistance

The contact R between each anode and the soil it's buried in. Usually the largest single component. Climbs as anodes consume and soil dries.

Soil resistivity

An *intrinsic property* of the soil itself, in Ω-cm. Not a circuit resistance you read with a regular ohmmeter — measured with a 4-pin Wenner setup. Drives anode-to-soil R directly.

Cable resistance

Between rectifier and groundbed. Usually fractions of an ohm — but at high current it eats meaningful voltage as IR drop (the EC-002 cable-drop case).

Coating resistance

The pipe coating's R per unit area. The whole reason coating exists from a CP perspective: high coating R means most of the current goes through coating defects (holidays) — exactly where protection needs to land.

HOW R IS MEASURED (OR BACKED OUT)

Almost never with the ohms scale on a regular multimeter.

None of the CP resistances above are read by clipping a generic ohmmeter to the rectifier output. The scales involved and the soil-electrochemistry effects mean the multimeter's internal ohmmeter circuit gives you a number that doesn't represent the system. The actual measurement methods:

Total circuit R — back out from V and I

Read rectifier voltage and current. Apply Ohm's Law: `R = V ÷ I`. Compare today's R to design R. (the Ohm's-Law diagnostic move from EC-002.)

Soil resistivity — 4-pin Wenner

Purpose-built soil resistivity meter with four pins driven in a line at equal spacing. Reads in Ω-cm. Used for design and periodic seasonal checks. *Procedure: later module.*

Anode-to-soil R — design + readings

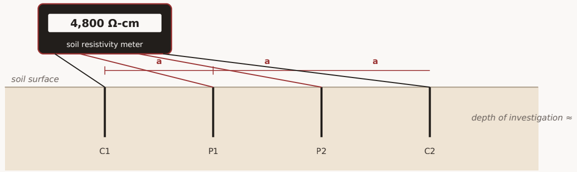
Calculated from anode geometry and soil resistivity at design time. Confirmed by reading rectifier V and I and comparing to design assumptions.

Coating R — specialized measurement

Direct coating-resistance testing, holiday detection (CT track), and integrity surveys. Not read at the rectifier. *Depth: later modules.*

THE 4-PIN WENNER SETUP — NAMED ONLY

The right tool for soil resistivity.



Four pins in a line at equal spacing "a" — the depth of investigation roughly equals the spacing.

What it tells you: the bulk resistivity of the soil at the location and depth corresponding to the pin spacing, in Ω-cm. Most pipeline corridors fall between 1,000 and 30,000 Ω-cm; very wet mineral soil can read 500 Ω-cm; dry sand can read 100,000+ Ω-cm.

> FORWARD POINTER
>
> ## Wenner method procedure + interpretation
>
> Pin spacings, multi-spacing layered profiles, seasonal variation, and the use of Wenner readings in groundbed design are covered in a later EC module.

The four readings every CP tech makes.

MEASUREMENT 1 OF 4

Structure-to-soil potential — a voltage.

SETUP

$Cu/CuSO_4$ half-cell pressed into moist soil near the pipe · pipe lead clipped to the test station header · multimeter on V DC · black to half-cell, red to pipe.

WHAT'S MEASURED

The difference in electrical potential between the structure and the soil at this location, referenced through the half-cell.

TYPICAL READING

`−0.85 V` to `−1.20 V` on a working impressed-current system. `−0.40 V` to `−0.65 V` on unprotected pipe.

WHAT IT TELLS YOU

Whether the pipe meets the −0.85 V criterion at this point. A series of these readings along the line builds the protective-status picture.

MEASUREMENT 2 OF 4

Rectifier output — a voltage and a current.

SETUP

Rectifier-mounted V meter and A meter (or shunt + portable meter on mV).

WHAT'S MEASURED

Two separate readings — source voltage the rectifier is putting on the cable, and current it's pushing into the system.

TYPICAL READING

12 V to 50 V on V; 5 A to 50 A on I. Both depend on system size and auto-tap setting.

WHAT IT TELLS YOU

Source-side state. V and I together let you back out total circuit R via Ohm's Law (the move you walked through in EC-002) and compare today's R to design.

> **The diagnostic move:** if today's V/I gives R_{total} 25% higher than design, something has changed in the loop — anode consumption, drier soil, loose connection. The reading doesn't tell you which; it tells you to go look.

MEASUREMENT 3 OF 4

Bond shunt current — mV across a calibrated shunt.

SETUP

Bond shunt (typically 0.1 Ω or 0.01 Ω) in series with a galvanic anode group, foreign-line bond, or test connection. Multimeter on mV DC across the shunt.

WHAT'S MEASURED

A voltage drop across a known resistance. Apply $I = V \div R_{shunt}$ to convert to current.

TYPICAL READING

A few milliamps to a few amps for a galvanic anode bond; up to tens of amps on heavier bonds.

WHAT IT TELLS YOU

How much current is flowing through that specific connection. Compared to design and prior readings, says whether the anode group is still performing.

MEASUREMENT 4 OF 4

Soil resistivity — a resistance, named only.

SETUP

Purpose-built soil resistivity meter with four pins driven in a line at equal spacing (Wenner 4-pin).

WHAT'S MEASURED

Bulk electrical resistivity of the soil, in `Ω-cm`. An intrinsic property of the soil, not a circuit resistance.

TYPICAL READING

500 Ω-cm (very wet mineral) to 100,000+ Ω-cm (dry sand). Pipeline corridors typically 1,000–30,000 Ω-cm.

WHAT IT TELLS YOU

Soil's intrinsic R per unit volume — drives anode-to-soil R, groundbed sizing, CP system design. Procedure depth: later module.

SIDE BY SIDE

The three quantities at a glance.

Qty	What it is	Where you measure it	What it tells you
V	Electrical pressure between two points	Cabinet output, between half-cell and pipe at TS, across a shunt, between two ends of a cable	Source state, protective status, IR drop, calibrated shunt readings
I	Rate of charge flow — does the protective work	Rectifier output (via shunt), bond shunts at TS, indirectly at structure surface (current density)	System output, anode performance, current reaching the structure
R	Opposition to current flow — sets the budget	Backed out from V and I (Ohm's Law); soil resistivity via Wenner 4-pin	System R vs design, soil conditions, groundbed health, coating integrity

Voltage requires a reference. Current does the work. Resistance sets the budget.

THREE READINGS, ONE DIAGNOSIS

Back at the test station — the trio together.

S-TO-S POTENTIAL

−0.94 V

$Cu/CuSO_4$, at TS-04. More negative than −0.85 V → meets criterion. The pipe is protected here.

RECTIFIER V

22 V

Source pressure on the cable. On a 24 V max rectifier, this is near its output ceiling — not much room left.

RECTIFIER I

12 A

Current the rectifier is delivering. Compared to 10 A design, slightly elevated — could mean coating defects or wetter soil.

$$R_{total} = V \div I = 22\ V \div 12\ A \approx 1.83\ \Omega$$

Compared to design R_{total} = 1.5 Ω, today's circuit is 0.33 Ω higher. Each reading individually answers one question; together they tell you the system's health. **That synthesis only happens when you can name what each reading is.**

KEY TAKEAWAYS

What you can do now.

- **Voltage** is electrical pressure between two points. The canonical CP voltage is structure-to-soil potential against Cu/$CuSO_4$. **−0.85 V is the standard floor.**
- **The Cu/$CuSO_4$ half-cell** is the practical default reference for buried-pipeline CP — stable, repeatable, well-correlated with decades of CP criteria.
- **Current** is the flow that does the protective work. It shows up at the rectifier output, at bond shunts, and at the structure surface (current density).
- **Resistance** isn't a single thing in CP. The four R's: anode-to-soil R, soil resistivity, cable R, coating R — each measured differently.
- **Total circuit R is almost always backed out** from V and I via Ohm's Law (EC-002), or measured with a purpose-built tool like a Wenner soil resistivity meter.
- **Three readings, one diagnosis.** S-to-S V tells protection state · rectifier V/I tells source state · combined they tell system health.

WHERE THIS COMES FROM

References & further reading

- **AMPP CP 1 Cathodic Protection Tester Course Manual** — the half-cell, structure-to-soil potential measurement, and the −0.85 V $Cu/CuSO_4$ criterion.
- **AUCSC Basic Course** — V/I/R foundations and field-measurement coverage of reference electrodes and CP criteria.
- **Peabody's Control of Pipeline Corrosion** — A.W. Peabody. CP criteria framework and survey/measurement practice.
- **AMPP CP 2 Cathodic Protection Technician Course Manual** — extended treatment with technician-level depth on field measurements, current density, and survey practice.
- **CP Survey Procedures** — practical procedural depth on close-interval surveys, depolarization, and reference-electrode practice.
- **Corrosion Basics: An Introduction** — broader textbook framing on the role of V, I, and R in CP design.

UP NEXT IN THIS RUNG

EC-004 — AC vs. DC Electricity: Characteristics and Differences

How AC and DC behave differently in CP-relevant contexts — why we use DC for protection, where AC influence shows up on pipelines, and how each appears at the meter.