EC-005 · MODULE 5 OF 22

Power and Energy in Electrical Circuits

From two readings on the cabinet to five numbers on the operations report.

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

BY THE END OF THIS MODULE

You'll be able to —

- Apply the **three forms of the power equation** — $P = V \times I$, $P = I^2 \times R$, $P = V^2 \div R$ — and pick the right form for the quantities you have.
- Calculate **energy in watt-hours and kilowatt-hours**, and convert to annual operating cost.
- Reason about **rectifier efficiency** and the wattage dissipated as heat inside the cabinet.
- Identify the **three places heat shows up in CP systems** — cabinet, cables, connections — and the loose-connection diagnostic.
- Walk one cabinet visit through to **five numbers**: protective wattage, utility load, annual kWh, annual cost, continuous heat.

A STANDARD CABINET VISIT

Two readings — taken with your own multimeter.

Meter on V DC, red lead on the (+) output lug, black lead on the (−) output lug: reads **22 V**. Meter on mV DC across the cabinet's internal output shunt (labeled `50 mV = 50 A`): reads **28 mV → 28 A** through the shunt.

22 V × 28 A = 616 W

Cabinet has built-in panel gauges. We don't trust those — they drift, they're rarely calibrated. Multimeter is the source of truth.

SAME CABINET · THE NAMEPLATE ADDS THE REST

Five numbers from two readings and a nameplate.

616 W	**Output power**	Protective wattage going into the soil-side circuit (V × I)
~670 W	**Input power**	What the rectifier draws from the AC line at 92% efficiency
~5,870 kWh	**Annual energy**	670 W × 8,760 hours per year of continuous operation
~$704	**Annual cost**	At a typical industrial rate of $0.12 / kWh
54 W	**Cabinet heat**	Continuous heat the enclosure has to dissipate (input − output)

Watts are work.
Kilowatt-hours are dollars.
Heat is the system telling you where the inefficiency lives.

WHAT WE'LL COVER

Two meter readings, one nameplate — and the math that makes them useful.

01
Power — three forms
$P = V \times I \cdot P = I^2 \times R \cdot P = V^2 \div R$

02
Worked examples
Cabinet, cable, diagnostic, full cycle

03
Energy
Wh and kWh · annual operating cost

04
Efficiency
Modern rectifier · output ÷ input · where the loss goes

05
Heat in CP
Cabinet · cables · connections

WHERE EC-005 SITS

Where the math meets the operating budget.

EC-001 named the **shapes** of CP circuits. EC-002 walked the **math** that runs inside them. EC-003 distinguished **V, I, and R** at the field-measurement level. EC-004 made the **AC and DC regimes** explicit. With those four in hand, every rectifier reading you take has settled meaning.

EC-005 turns those readings into the next set of numbers a CP tech actually has to manage: the **watts** the system is doing, the **kilowatt-hours** the meter is logging, the **dollars** on the bill that pays for them, and the **heat** the cabinet has to handle.

> **EC-006 picks up electromagnetism next** — the magnetic-field principles behind the transformer losses we'll name in this module. EC-007 finishes this rung with the full transformer treatment.

SCOPE DISCIPLINE

What's in scope today, what's already covered, what's coming.

Topic	Where it lives	Status here
Series / parallel circuit shapes	EC-001	Named at reference level only
Ohm's Law calculation drill	EC-002	Referenced and built on (V/I/R values feed power)
V/I/R distinction at the meter	EC-003	Referenced
AC vs DC regimes	EC-004	Referenced
Power and energy calculations	EC-005 (here)	In scope
Magnetic-field principles	EC-006 (next)	Forward-pointed (transformer loss physics)
Full transformer treatment	EC-007 (finishes rung)	Forward-pointed

PART 1 OF 5

Power — three forms, one quantity.

RATE OF ENERGY DELIVERY

One watt is one volt-amp.

Electrical power (**P**) is the rate at which electrical energy is delivered, used, or converted to heat. The unit is the **watt (W)**.

$$1\ W = 1\ V \times 1\ A$$

A current of one ampere flowing under a pressure of one volt delivers one watt of power. Higher voltage at the same current → more power. Higher current at the same voltage → more power. Both at once → multiplication.

ONE QUANTITY, THREE DERIVATIONS

Pick the form that uses the quantities you have.

$P = V \times I$

use when you know voltage and current

$P = I^2 \times R$

use when you know current and resistance

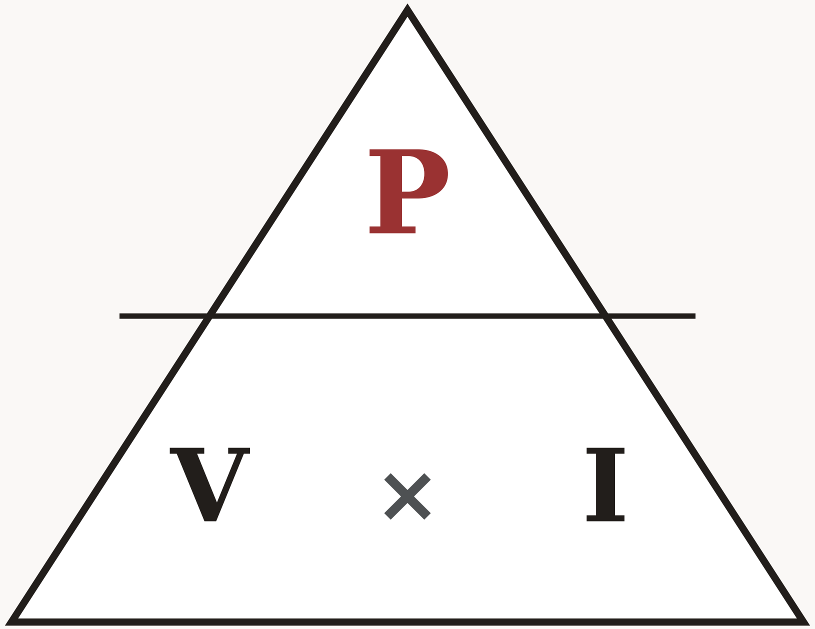
$P = V^2 \div R$

use when you know voltage and resistance

The three forms are algebraically the same equation. Substitute Ohm's Law ($V = I \cdot R$ or $I = V/R$) into $P = V \times I$ and the other two fall out. Use whichever matches the quantities on hand at a cabinet.

VISUAL MNEMONIC — COUSIN TO OHM'S LAW TRIANGLE

Cover the unknown. What's left is the operation.



cover the quantity you want · what's left is the operation

Cover P → V × I. Cover V → P ÷ I. Cover I → P ÷ V. The I^2R and V^2/R forms come from substituting Ohm's Law into P = V × I.

WHY THREE FORMS, ONE TRUTH

The same equation, two substitutions away.

Start with: $P = V \times I$

Swap V for I × R (Ohm's Law): $P = (I \times R) \times I = I^2 \times R$

Swap I for V ÷ R (Ohm's Law): $P = V \times (V \div R) = V^2 \div R$

Same quantity, three derivations. If your two-of-three V/I/R values are consistent (i.e., they actually obey Ohm's Law), all three forms will produce the same wattage. They cross-check each other.

PART 2 OF 5

Worked Example A — rectifier output power.

RECTIFIER OUTPUT, THE STANDARD CABINET MOVE

P = V × I — the bread-and-butter calculation.

SETUP · MULTIMETER READS 22 V AT THE OUTPUT, 28 A THROUGH THE SHUNT

Find the rectifier output power

Known: 22 volts (multimeter on V DC, leads on (+) and (−) output lugs) and 28 amps (multimeter on mV DC across the shunt). Unknown: P.

Apply: **P = V × I = 22 × 28 = 616 W**

Field meaning: 616 watts is the rate of protective electrical work going into the cable. Same calc runs at any cabinet — only the scale changes (12 V × 5 A rectifier on a short crossing or single tank → 60 W; 50 V × 40 A rectifier on a long pipeline run → 2,000 W).

PART 2 (CONT.)

Worked Example B — cable IR loss as heat.

CABLE AS ENERGY BUDGET

$P = I^2 \times R$ — heat dissipated in the conductor.

SETUP · 28 AMPS FLOWING THROUGH A 0.15-OHM CABLE

Find the heat dissipated in the cable

Known: 28 amps of current, 0.15 ohms of cable resistance. Want: how many watts of heat.

Square the current first, then multiply by R: **$P = 28 \times 28 \times 0.15 = 784 \times 0.15 \approx 118$ W**

Field meaning: 118 W (~19% of the rectifier's 616 W output) is the cable's tax on the budget — wattage that *isn't* doing protective work in the soil. Cable is warm to the touch on a hot day for exactly this reason.

WHY HEAVIER-GAUGE CABLE MATTERS

Doubling the current quadruples the heat.

at 28 A:
118 W heat

at 56 A:
470 W heat

Same cable, twice the current, **4× the loss**. Because `P = I² × R` scales with the square of current, high-current installations pay disproportionately for thin cable. Lower R cuts the loss directly; the I^2 term doesn't change.

Cable sizing is an energy decision dressed up as a hardware purchase.

PART 2 (CONT.)

Worked Example C — power from V and R.

THE DIAGNOSTIC MOVE

$P = V^2 \div R$ — when you have V and R, not I.

SETUP · 24 VOLTS AT THE RECTIFIER, 1.6 OHMS TOTAL CIRCUIT RESISTANCE

Find total system power without measuring current

Known: 24 volts at the output, 1.6 ohms total resistance. Unknown: total power.

Square the voltage, divide by R: **$P = 24 \times 24 \div 1.6 = 576 \div 1.6 = 360$ W**

Cross-check using $V \times I$ (current would be $24 \div 1.6 = 15$ A): $24 \times 15 = 360$ W ✓

Cross-check using $I^2 \times R$: $15 \times 15 \times 1.6 = 360$ W ✓

All three forms close on the same number. Most useful as a sanity check, or when working a design problem on paper before the system exists.

PART 2 (CONT.)

Worked Example D — the full cabinet-to-bill cycle.

FIVE NUMBERS FROM ONE CABINET VISIT

The full arc — output, input, energy, cost, heat.

616 W	**Output power**	P = V × I = 22 × 28 — the protective wattage
~670 W	**Input power**	Power in = Power out ÷ Efficiency = 616 ÷ 0.92 — the utility-meter load
~5,870 kWh	**Annual energy**	0.670 kW × 8,760 hours — what the meter logs over a year
~$704	**Annual cost**	5,870 kWh × $0.12/kWh — the operating-expense line
54 W	**Cabinet heat**	Heat = Power in − Power out = 670 − 616 — continuous thermal load

PART 3 OF 5

Energy — power times time.

FROM WATTS TO WATT-HOURS

Energy is power accumulated over time.

$$\text{Energy} = \text{Power} \times \text{time}$$

Standard unit: the **watt-hour (Wh)** — one watt delivered for one hour. The utility bill is in **kilowatt-hours (kWh)**.

$$1\ \text{kWh} = 1{,}000\ \text{Wh}$$

100 W for 1 hour = 100 Wh = 0.1 kWh. Same load for 24 hours = 2,400 Wh = 2.4 kWh. That's the math the meter is doing every minute.

FROM WATTS TO THE UTILITY BILL

Continuous load × hours-per-year × $/kWh.

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Annual kWh = (Power in kW) × 8,760
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A 670 W rectifier (0.670 kW) running continuously: `0.670 × 8,760 ≈ 5,870 kWh` per year. At `$0.12/kWh` that's **~$704 per year**.

> **Industrial electric rates vary** — anywhere from $0.05 to $0.20 per kWh across North America. Use the local utility's industrial-tariff rate when sizing a real budget. Each rectifier is small, but multiply across a system with two dozen rectifiers and the total adds up to a real operating expense.

PART 4 OF 5

Efficiency — output divided by input.

WHERE THE LOST WATTAGE GOES

Some portion of input power always becomes heat.

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Efficiency = Power out ÷ Power in
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Modern, current-generation rectifiers can be quite efficient — many designs operate well above 90%. Actual efficiency varies with rectifier type (silicon, switching, oil-cooled), age, cooling, and load. The percentage tells you how much input power becomes cabinet heat. Four sources of loss:

- **Transformer copper losses** — heat from current flowing through the primary and secondary windings.
- **Transformer iron (core) losses** — energy spent magnetizing the core every AC cycle (hysteresis + eddy currents).
- **Diode forward-voltage drop** — each diode in the rectifier bridge consumes ~0.7 V × current → heat at the diode.
- **Filter losses** — small amounts in the smoothing components.

> **EC-006 picks up the magnetic-field principles behind transformer losses.** EC-007 is the full transformer treatment. EC-005 names the loss sources without unpacking the physics.

PART 5 OF 5

Heat dissipation — a practical view.

THREE PLACES TO LOOK

Cabinet, cables, connections.

The rectifier cabinet

Transformer windings, transformer core, diodes, filter components. Distributed across internal hardware. Managed by the cabinet's vents, fins, and ambient air. Designed-for at modest levels (54 W in our example) up through much higher in larger units.

The cables

I^2R losses anywhere current flows through resistance. Header cable from rectifier to groundbed gets warm at high current. Bond cables at test stations are usually cool — small currents.

The connections

Cable lugs, bolted bus, splices. Clean and properly torqued = very low R, almost no heat. Loose or oxidized = local high-resistance spot dissipating substantial wattage in a small area.

HEAT AS INFORMATION

A hot lug is the math telling you something.

A loose lug at a rectifier output, or a corroded splice in a junction box, presents as a **local hot spot**. The math is the same $P = I^2 \times R$: same current, higher resistance at that point, more wattage dissipated as heat right there.

Why a hot connection is also a safety concern

A loose lug carrying 30 A can dissipate hundreds of watts in a small area. Enough to scorch insulation, soften plastic, or in extreme cases ignite combustible material near the cabinet. **A connection that's hot to the touch is both a CP performance issue and a fault to address.** Thermal scans of cabinets at scheduled maintenance catch these before they fail.

KEY TAKEAWAYS

What sticks.

- **Power** is rate of energy delivery, measured in watts. Three forms: `P = V × I`, `P = I² × R`, `P = V² ÷ R`. Same quantity, three ways to compute it.
- **Cable heat scales with the square of the current.** Doubling the current quadruples the heat. That's why heavier-gauge cable pays off when current goes up.
- **Energy = power × time.** kWh is what the utility bill is in. Continuous-running rectifier annual kWh = (kW) × 8,760.
- **Annual operating cost** = annual kWh × local industrial electric rate. Each rectifier small; system total is a real line item.
- **Efficiency** = output divided by input. Some portion of input power always becomes heat in the cabinet — transformer losses, diode forward-V drop, filter losses. The percentage tells you how much.
- **Heat shows up in three places:** cabinet, cables, connections. Loose lugs become local hot spots — both a performance issue and a safety concern.
- **Five numbers from one cabinet visit:** output power, input power, annual kWh, annual cost, continuous heat. Each routes to a different decision.

WHERE THIS COMES FROM

References & further reading

- **AMPP Cathodic Protection Training Materials** — Power calculations and rectifier sizing fundamentals for impressed-current systems.
- **Peabody's Control of Pipeline Corrosion** — Rectifier output, operating power, and field economics for CP.
- **AUCSC Short Course Materials** — Practical coverage of rectifier power, efficiency, and operating cost for field technicians.

UP NEXT (5 OF 7 IN THIS RUNG)

EC-006 — Electromagnetism and Magnetic Field Principles

The magnetic-field principles behind how rectifier transformers actually convert AC to DC — and the physics of the transformer copper and iron losses we named in EC-005.