Episode Book

EPISODE #5758

Why Your Outlet Is 120 Volts and Europe's Is 230

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SYNOPSIS

Why does the US run 120 volts and Europe 230? The answer isn't physics — it's a standards table, a diplomatic handshake, and a lamp. This episode digs into IEC 60038's dozen sanctioned voltage values, why 230/400 was a manufacturing compromise rather than an engineering optimum, and what the copper math says about dropping household voltage to 50. Plus: the "silent killer" of 240-volt equipment fed 230, and what all of this reveals about whether DC-native transmission is actually feasible.

TRANSCRIPT



Corn

Last episode we went down the DC transmission rabbit hole, and it ended somewhere interesting. Today we're still on the power thread, but we're looking at the other end of the wire. The voltage that actually shows up at your house.



Herman

The last mile. Or the last five hundred feet, more precisely.



Corn

Right. Daniel wrote in this week. And the arc of his question is basically this. The modern orthodoxy assumes electricity gets transmitted high voltage across grids, then stepped down to something like 100 volts, or 230 in Europe, or 400 for three-phase customers. But nothing in the laws of physics says power has to be transmitted as AC, and nothing says those particular numbers are mandatory.



Herman

Correct. Neither of those is a physical constant. They're standards.



Corn

He asked five things, so let me get them all out. One. What are the actual differences in delivery voltage between the US and the countries standardizing on 230 volts, including three-phase customers who take 400. Two. What are the broader implications of delivering different voltages to consumers. Three. If there's a safety case for lower household voltage, why don't we just transform it down to fifty volts. Four. Is there anything special about 110 and 230 volts electrically, or are those just the numbers the two systems happened to pick. And five. What does the logic of delivery voltage decisions tell us about whether DC-native transmission is actually feasible.



Herman

All five in one prompt. That's Daniel.



Corn

He noted we've done the history of why the US picked 110 to 120 in an earlier episode, so he's after the engineering logic underneath the numbers this time.



Herman

Good. Because the history only gets you partway. The history explains why 110 and 230 exist. It doesn't explain why you couldn't just halve everything tomorrow.



Corn

So where do we start?



Herman

With the correction that most people get wrong before they've even asked the question. The US is not a 120 volt country.



Corn

It markets itself as one.



Herman

It markets itself as one, and it says so on the little label on the back of the toaster. But look at what actually arrives at a house. You get two 120 volt conductors plus a neutral. Line to neutral, 120 volts. Line to line, 240. That's what feeds the oven, the dryer, the water heater, the big shop tools, the EV charger. So the American house already has 240 volts sitting in the panel.



Corn

So the difference isn't the voltage ceiling. It's where the split happens.



Herman

That's the whole thing. In Europe the delivery is 230 volts line to neutral and 400 line to line, and the three-phase runs to more of the house. In the US, single-phase split gives you 120 and 240, and three-phase generally stops at the commercial building. Same voltage family in the panel. Different decision about where to cut the ticket.



Corn

To be concrete for a listener picturing a map. The Americas run roughly 100 to 127. Europe and most of the world run 220 to 240. Japan sits down in the low family too, at 100.



Herman

Japan is the interesting case, because they're not low for historical accident so much as because they built their grid in the Edison era and never fully converted. Tokyo is 50 hertz. Osaka is 60. That's a separate headache.



Corn

And then there's the document that actually writes down the legal options.



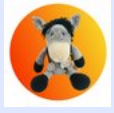
Herman

IEC 60038. That's the one Daniel's question is really pointing at. It's the standard that lists the sanctioned low voltage values. It's not just US versus Europe. It's a whole table.



Corn

So that's the standards table and where the numbers came from. But the table doesn't tell you why you can't just pick a lower number. That's the physics.



Herman

Let me lay the table out, because it's a menu. For 50 hertz three-phase, the sanctioned values are 230 volts three-wire, 230 over 400, 400 over 690, and 1000. For 60 hertz: 120 over 208, 240, 230 over 400, 277 over 480, 480, 347 over 600, and 600. And for



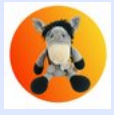
Herman (continued)

American single-phase split 60 hertz, 120 over 240.



Corn

That's more than two systems. That's a dozen.



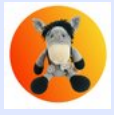
Herman

Which is the actual answer to "what are the differences." It isn't a US-versus-everyone-else story. It's a table with about a dozen entries, and every one of them is legal somewhere.



Corn

And 230 over 400 is the one that's supposed to win.



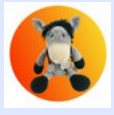
Herman

On paper it is. It's the number the IEC has been pushing since 1983.



Corn

Which is where the compromise story gets good. Because 230 isn't an engineering optimum. It's a diplomatic number.



Herman

Correct. It replaced two previous families — 220 over 380, and 240 over 415. The IEC widened the tolerance to plus or minus ten percent so both legacy ranges would fit inside the new band. So 220 and 240 both count as 230 if you squint.



Corn

That's not a standard. That's a handshake with numbers.



Herman

It's an unusually honest handshake. Edition 6 of IEC 60038 introduced 230 over 400 as the international target. Amendment one in 1994 made it mandatory. The deadline for countries on 220 over 380 or 240 over 415 to bring supply within plus or minus ten percent of 230 over 400 was 2003.



Corn

And did everyone make 2003?



Herman

Mostly, on paper. In practice it's still not done. The 2009 edition noted the transition was completed in many countries, but 220 over 380 and 240 over 415 systems persist. The 2021 amendment added 230 volts at 50 hertz and 230 over 400 at 60 hertz into the table, which is the body finally admitting the sixty-hertz world is going to have a 230 line too.



Corn

So twenty-three years after the deadline, the standards body is still tidying up.



Herman

A body with a clear mandate can't fully overwrite installed infrastructure. That's the lesson and it comes back later.



Corn

Why did they bother at all? What's the actual driver?



Herman

Manufacturing economics. Professor Alex Baitch of the University of New South Wales has been writing about this for years, and his summary of the rationale is the cleanest one out there. The point of the compromise was to assist manufacturers to only have to produce one range of products. His words: a major step forward in improving the overall economics of products.



Corn

So it's a supply chain decision dressed as a technical standard.



Herman

Entirely. You want one motor that works in Lisbon and Lima. You want one air conditioner for Singapore and São Paulo. That's the whole prize. It's the same logic behind USB-C. Nothing electrical about it.



Corn

And it isn't finished, which has costs. That's where Baitch's other phrase comes in.



Herman

Yeah. He calls the 240 versus 230 equipment mismatch a silent killer. Equipment designed for 230 volts but fed 240 loses life. Not dramatic failure. Just premature aging, quietly, in the field.



Corn

That's the honest cost of a compromise that didn't quite converge. You get a band, and equipment on the wrong edge of the band dies early.



Herman

And this is why Australia keeps coming up in the standards literature. Australian distribution transformers on a so-called 240 volt network often have a nominal output of 250 over 433. The maximum system voltage under the latest IEC edition for a 230 volt



Herman (continued)

system is 253. So 250 nominal plus the top of the tolerance band is really pushing at the ceiling.



Corn

How did we get two numbers in the first place?



Herman

Lamp technology and the War of Currents. Edison went to 110 volts DC because that's what his high-resistance carbon filament wanted in 1882. Pearl Street station opened in September that year and fed 110 volts DC to fifty-nine customers.



Corn

Fifty-nine customers. The entire American grid was a coffee shop's worth of people.



Herman

The whole installed base that mattered, at the time. Now, Tesla preferred 240 volts and 60 hertz. In Germany, AEG fixed on 50 hertz. And the reason they chose 50 over 60 is wonderful.



Corn

Go on.



Herman

Sixty didn't fit the metric standard unit sequence of one, two, five.



Corn

The frequency of an entire continent was chosen because 60 wasn't tidy in a metric table.



Herman

That's the level of decision-making in the 1890s. There's no physics to it. There's a preference for round numbers in whichever unit system you're using.



Corn

Okay. So. 110 and 230. Anything physically special about either?



Herman

No. And the cleanest proof is that Europe started at 120 too.



Corn

Say that again.



Herman

Originally Europe was 120 volts. Same as the US. And then they raised it, because raising voltage gets you more power with fewer losses and less voltage drop from the same copper diameter. The US considered doing the same thing, and balked at the cost of replacing every appliance already in American homes.



Corn

So the difference between continents isn't a difference in electrical theory. It's a difference in the cost of throwing out a working appliance.



Herman

That's the whole divergence. One side ate the swap. The other side didn't.



Corn

And the US spent the next eighty years drifting.



Herman

From 110 to 112 to 115 to 117, settling at 120 and 240 by 1967. And the driver for that drift was largely keeping incandescent lamps happy. The lamp makers kept pushing for a bit more voltage, the utilities accommodated, and the equipment followed.



Corn

The number wasn't chosen. It accreted.



Herman

It accreted around a preexisting installed base and a consumer lamp.



Corn

So the answer to "is 230 special electrically" is no. The answer to "is 120 special electrically" is no. They're both historical leftovers. And now I want to go after the safety argument, because that's the part where I think the orthodoxy deserves a poke.



Herman

Which safety argument?



Corn

The one that goes, lower household voltage is safer, therefore 120 is better than 230, therefore maybe we should go lower. That chain has a missing link.



Herman

It does. That second step is where the slip happens.



Corn

Let's do the copper argument first, because that's the harder constraint. For a fixed power, doubling the voltage halves the current. And because resistive loss goes as current squared times resistance, halving the current cuts the losses by a factor of four.



Herman

Losses fall with the square of current. So going lower costs you twice over. More current through the same wire means more heat per foot and a bigger drop at the far end. And the wire has to get fatter to keep the drop acceptable.



Corn

Give me the concrete version.



Herman

Two 10 kilowatt loads at low voltage draw about 166 amps total. That needs 1/0 gauge copper. Over a quarter inch in diameter, over three hundred pounds per thousand feet. If you double the delivery voltage you halve the current to about 83 amps, and that fits in number four gauge. Less than half the mass of copper for the same delivered power.



Corn

Three hundred pounds per thousand feet versus half that. That's the penalty for going lower, and it compounds every time you halve again.



Herman

And the copper isn't the only cost. Higher voltage demands thicker insulation, wider spacing, more clearance in the panel, better protective devices. So it's a genuine tradeoff. Copper cost and I squared R losses on one side, insulation and safety cost on the other. The equilibrium in the middle is where 120 and 230 both sit.



Corn

So when Daniel asks why not fifty volts — the answer is the copper mass would be absurd, the losses would be absurd, and the protection scheme would be enormous. For the same delivered power.



Herman

And notably, no serious engineering proposal exists to deliver households at fifty volts. The fifty volt figure only shows up as a safety threshold. The National Electrical Code defines low distribution system voltage as up to 49 volts, and above about fifty volts you're into real shock territory.



Corn

So it's not a candidate delivery voltage. It's a tripwire.



Herman

Right. American National Standards Institute extends low voltage all the way to 1000 volts, which is a different use of the same words. But the safety boundary that matters is around the fifty volt mark.



Corn

Okay. So now the actual question. Is lower household voltage actually safer in practice?



Herman

Here's where I want to be honest, because Daniel's instinct is right and the literature doesn't back it up cleanly. Every source asserts that lower voltage is safer. I couldn't find a single head-to-head statistical study comparing household electrocution rates between 120 volt and 230 volt countries.



Corn

Say that again, because that's a big gap.



Herman

There's no direct verdict on the question. The biomedical literature indexes electrocution case series. There's modeling. There's the IEC standard framework. But no study where the same population was split and fatality rates compared.



Corn

And this is a comparison that's been possible for a century.



Herman

The closest thing is the mechanism work. IEC 60479 models human body impedance at about five hundred ohms, with a heart-current factor to assess ventricular fibrillation risk. That's the framework for saying current through the heart is what kills you, not the voltage on the wire.



Corn

Which is exactly why "lower voltage is safer" doesn't follow automatically. Current through you is voltage divided by your body impedance, but the path through your body is the same either way. The difference is whether the current that flows crosses the fibrillation threshold.



Herman

And once you're above that threshold, adding headroom doesn't change the outcome for the person touching it. Both 120 and 230 are comfortably above the fibrillation threshold for a dry-hand-to-foot path. The gap is in the wet-hand case, and in the speed of the protective device.



Corn

That's what I'd want a study to show. Does a residual current device at 30 milliamps trip at the same speed and interrupt at the same point regardless of whether the supply is 120 or 230?



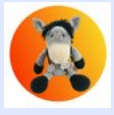
Herman

It does, but the physics of the fault loop changes. A 230 volt fault drives more current. So the protection might trip faster, or blow through it.



Corn

So there are two countervailing effects, and nobody has actually measured the net.



Herman

There are US numbers to compare against other countries, but they're not matched. Consumer product electrocutions averaged about forty-eight per year in the US over 2010 to 2013. NIOSH recorded five thousand three hundred forty-eight worker electrocutions from 1980 to 1992. That's around four hundred eleven per year.



Corn

So we have an American figure for consumer product electrocutions. And we have an American figure for worker electrocutions. We don't have the European counterpart number you'd need to compare.



Herman

That's the gap. It's possible the answer is not interesting — the rate difference is small because both are lethal in the wet path. But the premise has been asserted for decades. It's folklore until someone actually compares.



Corn

I'll say it plainly. If you're building a house today and the only argument for 120 over 230 is safety, and no one has actually measured the safety difference, then the argument is weak. But so is the argument for 230 over 120.



Herman

Which is the honest position. Both values are historical artifacts inside a copper and insulation tradeoff, and the safety premise is widely asserted and largely unmeasured. That's where the literature actually sits.



Corn

Now I want to bring this back to the DC question. Because that's the reason Daniel's asking.



Herman

The AC-versus-DC settlement in the 1890s was decided on the conversion equipment, not on the loss physics. Transformers step voltage up and down cheaply. That's the thing AC had and DC didn't. At the time, converting DC voltage at scale required power electronics that hadn't been invented yet.



Corn

So early DC systems were stuck at low transmission distances.



Herman

You couldn't step DC up. You had to run it at generation voltage, which meant the losses were brutal over any real distance. AC won because the equipment was cheap and simple, not because AC is lossless.



Corn

And in fact the loss comparison goes the other way.



Herman

For the same voltage and the same power over the same copper, DC has lower line loss than AC. Because AC suffers from the skin effect and from reactive power sloshing around in the lines. DC sees only the resistive loss in the copper.



Corn

So the settlement was economic, not physical.



Herman

Which is exactly what makes the question live. If the thing that picked the winner was the cost of conversion equipment, and conversion equipment has dropped in cost by orders of magnitude since the 1890s, then the settlement is at least worth re-examining.



Corn

So is anyone actually doing it?



Herman

Yes. There's a 2025 paper on arXiv — Subotić and colleagues — on dual-port grid-forming control for hybrid AC and DC systems. The claim is that a low-voltage DC distribution subsystem, interfaced by AC to DC converters, can serve as the sole interconnection between two separate AC distribution systems. So not a retrofit. The DC section is the only path between them. And they validated it in hardware, not just simulation.



Corn

That's a strong result, because it means the DC section isn't just a load hanging off an AC grid. It's a bridge.



Herman

That's the interesting part. A converter-based DC section can carry power in either direction, absorb and inject, and provide grid-forming services on both sides. That's the thing that wasn't possible when the decision was made.



Corn

So the logic question is right. The delivery voltage decision is a three-way tradeoff between copper mass, insulation and safety cost, and conversion equipment cost. And the numbers 120 and 230 sit inside that tradeoff, but they're not the optimum — they're where history left the system.



Herman

And the DC-native question is really a question about whether the conversion term has shrunk enough to change which side of the tradeoff you land on. If it has, then the low-voltage delivery question reopens.



Corn

Which brings me to something I want the listeners to hold onto. There's a real defect in the way 240-volt countries operate today.



Herman

Do you mean the Baitch point?



Corn

Yes. Equipment that's rated for 230 but is fed 240 gets prematurely killed by the top of the tolerance band. That's an active cost happening in the field right now, not a hypothetical.



Herman

It's exactly the same defect that would sink a poorly-planned DC-native deployment. If you send a nominal number but deliver a wider band, the equipment on the wrong edge of the band dies. The standard says 230. The outlet says 240. The motor says why.



Corn

That's the throughline for the whole episode. The number on the nameplate is not the number at the outlet.



Herman

That gap is where the actual engineering lives.



Hilbert

Yeah, I just want to correct one thing before you go any further. The number on the nameplate is never the number at the outlet. Not even close. I used to drive a feeder in the early nineties, rural line, eleven miles from the substation. Nominal at the tap was 124. Nominal at the last house was 112.



Herman

On the same feeder.



Hilbert

Different day, different load. A guy at the end put in a table saw with a capacitor start motor. Stalled on startup every spring, because the lights in his neighbor's house dimmed enough to make the motor unhappy. We didn't change the standard. We changed the tap on the distribution transformer feeding that section. Turned it up by one step. Solved.



Corn

One step on one transformer.



Hilbert

One step. Took twenty minutes. The motor ran fine for the next eleven years. The standards table never knew. The number on the paper was 120. The number he actually had was 112 in July, 119 in January, and 109 on a hot afternoon with everyone's air conditioning running.



Herman

The delivery voltage isn't a point. It's a band, and it's not constant across the day.



Hilbert

It never was. It was plus or minus ten on a cold afternoon with the feeder half idle. In summer it could go to minus fifteen on a long enough line. And you'd never know from reading the paper, because the paper tells you the value at the substation, or the value at the meter base on a test day with average load.



Corn

The tolerance band isn't the rare edge case. The tolerance band is where everyone lives.



Hilbert

Everyone at the end of a long line lives near the bottom edge of the band. That's what drove me up the wall every time somebody at a desk told me the number was the number.



Herman

That reframes the whole silent killer problem.



Hilbert

It does. Equipment rated at 230 and delivered 240 doesn't see 240 all day. It sees 235 in the morning, 242 when the sun's up, 238 in the evening. It's the excursions that kill it. The 242. And no standards table tells you how often a 242 is going to happen. Just the distribution engineer and the tap chart.



Corn

The actual voltage delivered to a customer is a curve, not a number.



Hilbert

A curve that you draw on a napkin. Yeah. And that's why the argument about whether we should all be at 230 or 120 misses the point. You can deliver either number with a swing of twenty volts depending on the feeder, the season, and what the guy at the end of the line is running.



Herman

Which means a DC-native grid would have exactly the same problem.



Hilbert

Worse, because DC doesn't have taps the same way. You can't just step a DC feeder up by one turn on a transformer. You need electronics at the end of the line. Which means the conversion equipment has to be field-serviceable, and it has to sit in the weather, and it has to be maintained by someone.



Corn

Someone has to be willing to drive out and turn one step when the motor stalls.



Hilbert

Someone always has. That bit never shows up in the paper, but it's what actually keeps the lights on. Anyway — sorry, one second. Corn, your mic's a little hot on the plosives, can you pull back an inch? Okay. Anyway, the guy with the saw, he called me every April for three years. It was the same conversation. And it was always one step.



Herman

You kept going out.



Hilbert

Yeah, I kept going out. It was an eleven mile drive on a good road. That's a small thing to do to keep somebody running a saw in their garage.



Corn

The number at the end of the wire is the number somebody has to maintain.



Herman

Which is a better mental model than the standards table.



Corn

Alright — the thing I keep circling is the safety question. We ran the numbers on copper, we ran the numbers on losses, and both say lower household voltage is bad. But the safety premise is the one everybody reaches for, and we couldn't find the study. So either there's a study out there we missed, and it's sitting in someone's drawer, or the premise is just folklore that's been repeated so often nobody's bothered to check it.



Herman

The DC question is the one I want to leave open. If the thing that ended the AC-versus-DC fight in the 1890s was the cost of conversion equipment, and conversion equipment has collapsed in cost, then the settlement is only as stable as the equipment that made it. The standards body couldn't move the last twenty percent of the world off 220 over 380 in two decades. Imagine what a DC-native grid would have to overcome.



Corn

The underrated lesson of IEC 60038 is that you can't overwrite installed infrastructure with a memo. That's a warning for anyone sketching a DC grid on a whiteboard.



Herman

Not a warning. A time scale.



Corn

Before we go, one thing that didn't fit. The single most interesting adjacent number from all of this. In IEC 60038, the maximum system voltage for a 230 volt nominal system is 253.



Herman

The nominal is 230 and the ceiling is 253 volts. That's the top of the plus ten percent band, on the highest-tolerance system in the standard.



Corn

The actual operating target for a "230" network includes a value twenty-three volts above the number printed on the device.



Herman

Which is a heroic amount of headroom to build into a system. But it's the price of getting 220 over 380 and 240 over 415 to sit inside the same standard. You don't get one number. You get a band, and the band is the standard.



Corn

That's a good place to leave it. Thanks to Hilbert Flumingtop for producing, and for the correction about the tap chart.



Herman

That was a real correction.



Corn

If you've enjoyed the episode, a review helps other listeners find the show. Everything lives at my weird prompts dot com. This has been My Weird Prompts, the human-AI collaboration podcast. We'll be back soon.



Herman

Take care.