Episode Book

EPISODE #5757

Why the Grid Still Runs on AC When DC Won

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SYNOPSIS

Thomas Edison lost the war of the currents because you couldn't change DC's voltage — but modern power electronics can convert DC at eleven hundred kilovolts, and HVDC lines now lose half as much power over distance as AC. So why does the grid still run on alternating current? This episode traces the transformer that decided a century of infrastructure, the 2012 circuit breaker breakthrough that made DC networks possible, and the four practical constraints that still cap DC voltage today. The answer isn't physics. It's a century of installed copper.

TRANSCRIPT



Corn

A forty-eight volt adapter where a twelve volt one belonged. That's the whole story. A fiber modem, a puff of the wrong electricity, and a dead line for however long it took to get a replacement.



Herman

And he's not even mad about the modem, really.



Corn

No, he's mad that it made him realize he had no idea what the ceiling on DC actually is. Which, fair. So Daniel wrote in, and this is worth getting right. He says we mentioned on a past show that telecoms has run on forty-eight volt DC for about as long as there's been a telephone exchange, and that data centers are now experimenting with high-voltage DC, up around four hundred volts, which is the voltage three-phase AC gets distributed at. He'd filed the whole thing under laws of nature. Grid AC, house wiring AC, power bricks make it DC at the last second. And the words "high voltage DC" caught him off guard, because the highest DC he had ever personally met was that forty-eight volt adapter. So he assumed forty-eight was roughly the ceiling on the output side.



Herman

And it isn't.



Corn

It isn't. So he wants to know whether an electrical grid could run entirely on DC. Which of the historical reasons for picking AC have gone away or stopped mattering. Whether any electrical constraint actually caps DC voltage. How much inertia the existing transmission network creates against changing anything. If we did imagine a grid where DC arrives at the wall socket, what voltage the outlets would be. And what adapter replaces the power brick if most devices are just stepping DC down instead of making it from AC.



Herman

That's five questions.



Corn

Six, by my count. And the fried modem is the perfect way in, because the reason that adapter existed in the first place is the same reason the grid runs on AC.



Herman

Right, and that's where the good stuff is. Because the AC versus DC story is not a story about which current is better. It's a story about which current is easier to change the voltage of. One property, decided a century of infrastructure.



Corn

And the thesis we're testing today...



Herman

Almost every historical argument for AC has been overturned by power electronics. And the grid is still AC. So the barrier isn't physics. It's the installed base.



Corn

Then let's start where it actually got decided. Why did the grid settle on AC in the first place?



Herman

Because of the transformer. That's it. A transformer works by electromagnetic induction, which means it needs a changing magnetic field. AC changes direction continuously, so the field is always moving, so the transformer works. A transformer cannot pass DC current at all. Not inefficiently, not expensively. It doesn't do it. Steady current makes a steady field, a steady field makes nothing happen in the secondary winding. So in the eighteen eighties you had a choice: transmit at whatever voltage your generator produced, or have no way to change it along the way.



Corn

Which is why you can't just crank the voltage up and save copper.



Herman

Edison's Pearl Street station, eighteen eighty-two, ran a hundred and ten volts from the generator all the way to the socket. Now think about what that means for loss. Voltage is low, so current has to be high for the same power, and line loss scales with the square of current. So you need enormous copper conductors, and your useful radius is under a mile. Which is why Edison's plants had to sit in the middle of population centers. He wasn't building a grid, he was building a series of islands.



Corn

A mile. You could walk the extent of the system.



Herman

In the time it takes to make coffee. And Westinghouse and Stanley demonstrated the alternative at Great Barrington, Massachusetts, March eighteen eighty-six. Five hundred volts on the line, stepped down to a hundred at each building, circuits up to about seven miles. Same copper, seven times the reach, because they could change the voltage.



Corn

So the transformer isn't a detail in this story. It's the whole reason.



Herman

It's the load-bearing fact. Everything else is decoration. And there were secondary reasons that stacked on top. AC generators were more efficient and could be built much larger. Tesla's induction motor patents, licensed by Westinghouse in July eighteen eighty-eight, gave you a complete system where you generate AC, transmit AC, and run motors on AC without any conversion step at all. That's an integrated product, and DC didn't have an answer to it.



Corn

There's a piece of this that never makes it into the version taught in school, which is that it was a business fight, not a technical contest. Edison didn't lose because his engineers were wrong.



Herman

He lost because he was selling a system built on one hundred and ten volts, and the other system scaled. But the campaign he ran was ugly. His side, through a man named Harold P. Brown, publicly electrocuted dogs and a horse to argue that AC was deadlier. And they colluded to have the first electric chair powered by a Westinghouse AC generator, to associate the technology with execution in the public mind.



Corn

The first electric chair as a marketing device.



Herman

It was a marketing device. And Westinghouse's reaction to the botched first execution was, "They would have done better using an axe." Which is a hell of a quote. And Edison himself, much later, told William Stanley's son, "Tell your father I was wrong."



Corn

Twenty-two years later.



Herman

So the man who lost the war eventually conceded, and he was right to.



Corn

Now here's the part that surprised me when I first read it. DC didn't die. It hung on.



Herman

It hung on for generations. Con Edison was still supplying DC to customers in New York City, mainly for elevators, until November fourteenth, two thousand seven. That was the last DC utility distribution in New York. Helsinki ran DC until the late nineteen forties. Stockholm until the seventies. Broadway theaters used DC dimming until nineteen seventy-five. This is not a nineteenth century curiosity. There are people listening to this who were alive when New York had a DC grid.



Corn

So the war was won, but the losing side kept a few towns.



Herman

Kept a few buildings, really. And the reason is instructive. Every one of those holdouts existed because the equipment in the building assumed DC, and ripping out the equipment cost more than keeping the supply.



Corn

Which is the inertia argument in miniature. Before we even get to the big grid.



Herman

It's the same argument at every scale. And that's the setup for the reversal, because here's the thing. Almost every reason AC won has since been overturned. Start with the big one. "You can't change DC voltage" is dead. Modern power electronics can convert AC to DC and DC to DC at very high power and very high voltage. Thyristors, IGBTs, IGCTs, and especially modular multilevel converters. Those are what make modern high-voltage DC transmission possible at scale.



Corn

So the exact capability that lost Edison the war is now a commodity.



Herman

It's a commodity you buy from a vendor. Now the second historical problem, and this one was nastier. "DC can't be interrupted." When a circuit breaker opens on an AC line, the arc that forms between the contacts self-extinguishes twice per cycle, because the current crosses zero and at that instant there's nothing sustaining the arc. That's about a hundred crossings per second at fifty hertz. On DC you never cross zero. The arc just keeps going. So for a century DC was fine for point-to-point transmission where you could shut the whole thing down, but you could not build a mesh with it, because you couldn't isolate a fault.



Corn

So the reason DC couldn't be a network was switching, not transmission.



Herman

Switching. And that broke in November two thousand twelve, when ABB announced the first ultrafast hybrid HVDC circuit breaker. It combines semiconductor switching with a mechanical switch, so it can interrupt a DC fault in a couple of milliseconds. That announcement is the unlock for multi-terminal DC grids. Without it you have point-to-point lines. With it you have a network.



Corn

And the loss argument flipped too, didn't it.



Herman

It flipped. For long lines, DC loses about three and a half percent per thousand kilometers. AC at the same voltage loses around six point seven percent. The reason is that DC carries only active power. There's no reactive power, no phase shift between voltage and current to account for. And no skin effect, so the current uses the whole conductor instead of crowding toward the surface.



Corn

Half the loss. On a thousand kilometer line.



Herman

Roughly half. And it gets better. For cables, submarine cables especially, DC isn't just cheaper, it's the only thing that works. An AC cable behaves like a big capacitor, so it draws charging current that grows with the length of the cable, and past a certain distance the charging current eats the entire capacity of the conductor. You can't push power through it. DC charges that cable capacitance once and then it's done. That's why every long undersea link is DC. NorNed, the North Sea Link, all of them.



Corn

And the interconnection argument.



Herman

Also reversed. HVDC is now the standard way to link grids that aren't synchronized. Japan runs fifty hertz in the east and sixty in the west, and the only thing joining them is DC. The Eastern, Western, Texas, and Quebec interconnections in North America are tied together with DC. The UK to the continent is DC. When the two ends don't agree on frequency or phase, DC is the translator.



Corn

So let's put the scoreboard up. You can't change DC voltage, false. DC can't be interrupted, false, at least since two thousand twelve. DC loses more over distance, backwards. DC can't do cables, backwards. DC can't interconnect grids, backwards.



Herman

Every single one. Which lands exactly on Daniel's presumption, and he's half right. Almost every historical reason for choosing AC is gone or far less relevant. So if the physics no longer blocks DC, the question becomes what actually does. And the answer is a century of installed copper.



Corn

Okay, to Daniel's first question then. Is there any electrical constraint that caps how high DC voltage can go?



Herman

There is no fundamental cap. None. China is running ultra-high-voltage DC at plus or minus eleven hundred kilovolts on the Zhundong to South Anhui and Changji to Guquan lines. Over three thousand kilometers, around twelve gigawatts of capacity per line. That is the highest-voltage transmission in the world, and it's DC. For comparison, the biggest AC transmission lines in service are running at about a third of that voltage.



Corn

Eleven hundred kilovolts. That's not a rounding error above the forty-eight volt adapter.



Herman

It's a factor of twenty-three thousand. And it's not even a new idea. Thury systems were running a hundred to a hundred and fifty kilovolts DC by nineteen oh six. The Elbe Project, planned in nineteen forty-one, never finished, was designed at plus or minus two hundred kilovolts. So people have known DC can go high for over a century. They just couldn't switch it or convert it cheaply until recently.



Corn

Then what actually limits it? Because something has to.



Herman

Practical constraints, and there are four that matter. First, insulation and corona. Under sustained DC stress, corona discharge behaves differently than under AC. Instead of particles oscillating back and forth, you get a constant wind of ions drifting one direction, and negative corona generates more ozone. So the insulator design problem is harder for DC, and you can't just take the AC insulator and run DC through it.



Corn

Contamination and tracking issues change too, I'd imagine.



Herman

Everything about surface behavior changes when the field never reverses. Second constraint, arc extinguishing and switching, which we covered. Third, converter cost. Converter stations are expensive, and they have limited overload capacity, so you can't push them the way you push a transformer. And crucially there's a break-even distance. Below about fifty kilometers for submarine cables, or six hundred to eight hundred kilometers for overhead lines, the losses in the converters exceed what you save on the line. So DC only pays off at distance or underwater.



Corn

Which is the opposite of where most of the grid lives.



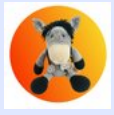
Herman

And fourth, multi-terminal complexity. This is the subtle one. On an AC network, power flows according to physics. Impedance and phase angle determine where it goes, and it self-balances. On a DC network, power flows where you tell it to. Every converter has to be actively controlled, with good communication between them. There's no passive fallback. So multi-terminal DC grids are rare and they need robust controls, because if the communication fails you have a problem with no natural answer.



Corn

So there's no law of physics stopping you, and four very expensive engineering problems in the way.



Herman

Four expensive problems, all solved, all costly. Which brings us to Daniel's second question. What would it take to convert a country's grid to DC? And the answer is brutal.



Corn

The wires aren't the problem.



Herman

The wires are the cheap part. HVDC terminal stations are the expensive part, and the line itself is actually cheaper than an equivalent AC line. So converting means rebuilding essentially every substation and adding converters at every generation site and every load center. You're not replacing copper. You're rebuilding the entire control and conversion layer of the grid. And then the economics fight you, because break-even says DC wins at distance, and a distribution network is the exact opposite of distance. Short runs, many taps, lots of little loads. Every one of those is a converter you have to buy and maintain, and none of them save you anything on line loss.



Corn

So a fully DC distribution grid is the worst case for DC.



Herman

It's the worst case for DC. Which is a counterintuitive result. The technology that wins on a three thousand kilometer line loses on a two hundred meter run to your kitchen.



Corn

And that's before you account for the fact that everything plugged in assumes AC.



Herman

Every appliance, every motor, every transformer, every protection relay was built on the assumption of a sinusoid at fifty or sixty hertz. The grid is a globally standardized, interoperable system. Voltage standards, frequency standards, protection coordination, all of it designed around AC. So the realistic path isn't replacement. It's hybridization. And it's already happening.



Corn

Which is where the data centers come in, and where Daniel's question actually lives.



Herman

This is the good part. The grid is quietly becoming a mixed AC and DC system. HVDC links embedded inside AC networks. Offshore wind farms collecting on DC. DC microgrids. DC data centers. Nobody is announcing a DC grid. It's being assembled around the edges.



Corn

So now the speculative payoff. If power arrived at wall sockets as DC, what voltage? And I want to flag that there are real anchors here, it's not a guess.



Herman

There are strong anchors. Forty-eight volts is the de facto standard for telecom and data center DC distribution, and it's over a century old. Telephone exchanges have run on minus forty-eight volts DC, negative polarity, positive grounded, for generations, and the reason for the negative polarity and the grounding is to prevent electrolysis deposition on the conductors. That's a hundred years of operational experience at that voltage.



Corn

And PoE sits in the same band.



Herman

Power over Ethernet standardizes DC distribution over data cabling at forty-four to fifty-seven volts. And the PoE advocates have a slogan I enjoy. Their stated goal is to banish the wall warts. Replace a hundred individual AC adapters with one central supply and a lot of cable.



Corn

Which is exactly the argument Daniel was reaching for.



Herman

It's the same argument. And then USB Power Delivery, which is the one that should actually get your attention, because it already delivers up to two hundred and forty watts at up to forty-eight volts over USB-C. That's a consumer-scale DC distribution standard that arrived while nobody was watching. Five volts, nine, fifteen, twenty, twenty-eight, thirty-six, forty-eight. It's already standardized the ladder.



Corn

So forty-eight volts has a hundred years of telecom, PoE, and USB-PD behind it.



Herman

It has the entire low-voltage DC ecosystem behind it. But here's the tradeoff. Forty-eight volts at high power means very high current, and high current means thick conductors. Which is the exact reason Edison's hundred and ten volt DC needed fat copper. Low voltage and high power are enemies.



Corn

So you'd want to go higher, and the data centers give you the number.



Herman

Around four hundred volts DC. And the reason data centers are moving there is precise. Four hundred volts is close to the peak of the three-phase AC that feeds the building, so if you rectify three-phase four hundred and thirty volts, the DC bus sits near four hundred, which means fewer conversion stages between the utility feed and the IT load. Every stage you remove is loss you don't pay and hardware you don't buy.



Corn

So it's not an arbitrary number. It's matched to what's already coming in the door.



Herman

It's matched to the input. And that gives you the two candidates. Roughly forty-eight volts if safety and compatibility with the existing DC ecosystem dominate. Roughly three hundred and eighty to four hundred volts if efficiency and conductor size dominate, and that's where the industry is actually heading. But four hundred volts DC is a dangerous voltage. It doesn't let go. There's no zero crossing to release a grip or extinguish an arc, so the safety design has to be much more serious than for the equivalent AC.



Corn

Two very different sockets depending on which goal you pick.



Herman

Two very different sockets. And I'd guess the honest answer is both, in different places. Forty-eight volts where a person might touch it. Four hundred volts where the equipment is sealed and the current is high.



Corn

Last question. What replaces the power brick?



Herman

A DC to DC converter, and specifically a buck converter, which steps voltage down. So here's what a modern brick actually does. It takes AC in, rectifies it to DC, chops that DC into high-frequency AC, pushes it through a small transformer, and then rectifies it back to DC at the voltage the device wants. The transformer is small because the frequency is high, and that's the trick that made bricks light instead of the size of a shoebox.



Corn

And if the input were already DC?



Herman

You skip the first rectification stage. The adapter becomes a pure DC to DC converter. Buck converters are efficient, typically between seventy-five and ninety-eight percent, using an inductor and fast switching instead of burning off the excess as heat the way a linear regulator does. That's the difference between a brick that's warm and a brick that isn't.



Corn

But the transformer doesn't go away.



Herman

The transformer doesn't go away if you need galvanic isolation, which is the safety barrier between the grid and the device you're holding. To get isolation from a DC input, you have to convert DC to high-frequency AC internally, pass it through a transformer, and rectify it back. So an isolated DC to DC adapter is not dramatically simpler than today's brick. It removes the input rectifier. That's it. The non-isolated ones inside phones and laptops are simpler and cheaper, but they're not the wall adapter.



Corn

So the real win isn't the adapter. It's where the conversion happens.



Herman

The real win is centralization. Instead of hundreds of millions of individual bricks each doing their own AC to DC rectification, you do the AC to DC conversion once, centrally, and distribute DC. That's the PoE argument exactly. Fewer conversion stages overall, central management, and less electronic waste from a billion wall warts in a billion drawers.



Corn

Now the cautionary tale, because Daniel's fried modem is the whole risk model in one object.



Herman

It's the perfect illustration. DC is polarity sensitive. AC is not. You can plug an AC plug in either way and it works, because the current reverses sixty times a second anyway. Do that with DC and you've reversed the polarity, and depending on the device, that's either nothing or a dead modem. And voltage matters in a way that's less forgiving, because there's no negotiation. A forty-eight volt adapter into a twelve volt device will destroy it instantly. Which is exactly what happened.



Corn

A DC grid needs voltage negotiation.



Herman

It needs what USB Power Delivery and PoE already do. Handshaking. The supply asks what the device wants, the device answers, the supply delivers that voltage. And standardized connectors so that a forty-eight volt plug physically cannot go into a twelve volt socket. The technology exists. It's in the cable charging your phone. It just has to become the norm everywhere instead of the exception.



Corn

The answer to Daniel's question is not a physics answer.



Herman

It's never been a physics answer. It's an infrastructure answer, and the infrastructure is winning by default.



Corn

Which raises something I keep circling. Where does the DC socket actually come from?



Herman

Not from the grid.



Corn

Right. It comes from the device side. Nobody's going to rebuild a national grid so your laptop can skip a rectifier.



Hilbert

The rectifier was never the problem. I had a question about that, if it's the right moment.



Hilbert

You said forty-eight volts has a hundred years behind it. I spent a couple of years looking after a DC plant, and I kept a log of every fault we had. Sixteen faults in two years. Fourteen of them were one cell in the string going high-resistance, and the other two were a loose inter-cell link. Not one of them was the rectifier. The rectifiers just sat there. What actually took the plant down was the battery, and nobody logs the battery.



Corn

Sixteen faults, and you kept the list.



Hilbert

I kept the list. And the voltage the plant actually sat at, measured at the bus, was fifty-three and a half. The load wanted forty-eight. The difference is what charges the string. That's the part nobody tells you. The number on the label and the number on the bus are not the same number, and the gap is the thing you're maintaining.



Herman

That's the tradeoff in one number. The float voltage is above nominal because the chemistry needs it, so every load on that bus lives at a permanently elevated voltage, well above what the nameplate says, and the equipment has to tolerate that for years.



Hilbert

It does tolerate it. Mostly. What it doesn't tolerate is somebody swapping a link without torquing it. I had one of those. The man was in a hurry because the lift was waiting. Two weeks later, high resistance on the joint, and we found it on the monthly check, not on an alarm. That's why I kept the log. The alarm only tells you when it's already gone.



Corn

Your answer to "what caps DC" is that nothing caps it, and the boring part is what breaks it.



Hilbert

The boring part is what breaks it. Anyway. The level on your track two is running about three decibels hot. I'll fix it in the edit. Carry on.



Herman

So the grid's future is hybridization, not conversion.



Corn

Which means DC wins everywhere except the last mile.



Herman

DC wins everywhere except the last mile, and the last mile is where the interesting part is, because that's where it's already arriving, just not from above. It's coming from the device side. USB-C has quietly standardized a DC ladder up to forty-eight volts. PoE has been pulling DC through data cable for years. Data centers are standardizing on four hundred. Nobody voted for any of it. It just shipped.



Corn

If you take one thing from this, take this. The War of the Currents was never settled on the merits. It was settled by a transformer, and the transformer's objection expired decades ago. What's still standing isn't the physics. It's a hundred and forty years of installed



Corn (continued)

copper.



Herman

The copper wins until the copper gets replaced anyway, which is why the DC socket will show up in a wall wart's grave rather than in a utility's master plan.



Corn

If you want to push back on any of that, or if you've fried something with an errant adapter and would like to confess, email us at show at my weird prompts dot com. The show's posted daily, all of it's at my weird prompts dot com, and a review helps other people find it.



Herman

Thanks to producer Hilbert Flumingtop for keeping the whole thing running, and for the level note.



Corn

This has been My Weird Prompts, the human-AI collaboration podcast. We'll be back soon.