Power Networks for Dummies

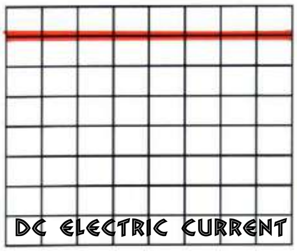
There's a lot of talk on both sides of politics about **electricity.** *How to make it, how to use it. However* not many stop to think about *how we move it around*.

Why can't we just replace a couple of big coal fired power generators with thousands of small renewable ones and still expect the lights to stay on? What's all this talk about Network Stability? Does it really matter where the power goes in and where it comes back out?

We need an *intimate understanding of our power networks* if we are going to understand why our network is the way it is. In this article we're going to attempt the impossible : to educate you about how electricity networks work, without using too much mathematics. To do this we need to do two things. First, we need to explain the difference between *AC and DC*. Then we need to learn about how electricity networks have developed here on planet Earth, so we can understand why things are the way they are!

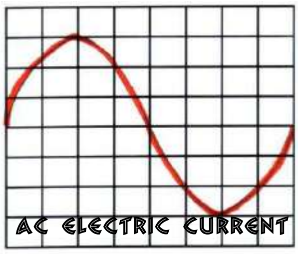
AC/DC

OK so AC/DC might be the name of the most famous rock band in the world. However "AC" and "DC" are also *electrical terms*. If you go and study electricity, you'll spend your first year learning all about "DC". When you start your second year class, they'll promply tell you that *everything you just learned is a load of crap and that now, you're going to learn about AC electricity*!



The reality is that ***DC electricity* is just *AC electricity* with a *frequency of zero***.

Electricity is generated when an *electric wire* crosses a *magnetic field*. It's not the wire or the field that generate the electricity, it's **the *change***. When we generate electricity using magnetism, the *current constantly changes both it's strength and direction*. The change is associated with the *speed that we move the magnets and wires around each other*. When we talk about this in electrical terms, we use the word **"frequency".**



The *frequency* of the electricity we use in our power networks is "50Hz" (60Hz in US/Japan). This means *the electric current* ***goes back and forth 50 times per second*** *and is known as "AC".*

DC electricity on the other hand, ***has no frequency***. The current *remains constant*. Power sources such as **batteries** and **solar panels** generate **DC**.

So there you have it. **AC is constantly changing, DC remains static**. Just remember those two things and we'll be just fine….

POWER NETWORK HISTORY

DC MOTOR / GENERATOR

In the earliest days of electricity there were only **batteries** which put out a *DC current*. Once the relationship between electricity and magnetism was understood, the earliest *electric motors* were born. These used a *mechanical "commutator"* to *change the polarity of the DC current* from the batteries *as the motor went around*. A *commutator* is basically a *mechanical inverter* which *creates AC current* from the DC.

About the same time as the invention of the DC motor, it was discovered that you could do the same thing in reverse. You could *turn the motor in to a generator,* simply by *spinning it.* Here, commutator *converts the AC current back in to DC*.

The very first "power networks" were all DC simply because at the time that was what everybody understood best. When Thomas Edison electrified Menlo Park in New York, he used 110v *DC current* created from commutator generators. Everything was fine all the while his generator was located right next door to the park and the power didn't have to travel very far.

However before long, Edison came across the *problem of transmitting his electricity over longer distances* to new customers who weren't next door. He would either have to build more power stations, or use much thicker, expensive copper cables to minimise the *huge power loss* that resulted of using such a low voltage (110v).

One alternative was to use a “motor generator” to convert the 110v DC to a much higher voltage. This would enable Edison’s DC network to distribute the power over longer distances using much thinner cables without huge power loss. However this had the disadvantage that he would *need another motor generator at the other end of the high voltage DC line*. One to *convert it up* and another to *convert it back down again*.

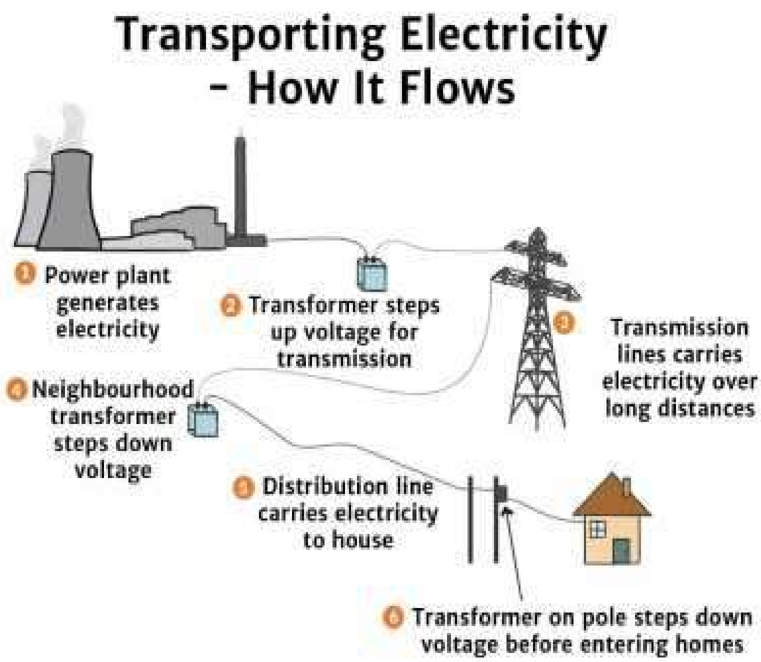
Unfortunately the *power loss* across the two motor generators would have been about as bad as if he had just used 110v all the way! That’s because all the rotating machinery, copper coils, fans and the commutators in the motor generator sets *all use power.. Lots of power.* So much so that by the end, there wouldn’t be much left for the customer to actually use!

In Edison’s time, power conversion from one voltage to another and back again. was very difficult. Rotating machines as a power converter, are *very inefficient.*

Then along came this guy called **Nikola Tesla.** Edison’s DC didn’t stand a chance.

Regardless of what people might think about Tesla’s crackpot ideas around broadcast power which have since proven to be horrendously wrong, **Tesla is still referred to today as the father of AC power network design**. It was *Nikola Tesla* who first demonstrated that it was practical to **dispense with the commutators altogether, and just transmit and use electricity in the form that the generators originally created it—as *AC current.***

Typical Australian *pole transformer*. The “200” denotes the capacity—in this case 200kVa, enough power for about 16 typical homes.



Not only does Tesla’s AC network eliminate the “lossy” commutators, it also means the we can easily convert between high and low voltage through use of **transformers**. *Tesla’s three phase AC power network forms the core of every power network in use in the world today*. There are squillions of his brushless and commutator-less “squirrel cage” AC induction motors in use everywhere.

Tesla’s *AC distribution network* allows the use of efficient ***transformers*** to *convert power to very high voltages* for transmission over very long distances. Other transformers are then used to convert the power back down again to lower voltages at the customers’ end where the power is used.

This design works very well, all the while there is *only one generator*. However because the current is AC and “always changing”, as soon as we intend to ***connect two generators together*** in a ***network***, things suddenly become very complicated.

Connecting multiple generators together was very easy with Edison’s old DC system. Since the current is always travelling in the same direction, we can just connect another generator in parallel and start spinning it. However *with an AC network*, both generators not only have to be spinning at exactly the same speed, but *the* ***AC current they produce, has to be synchronised in exactly the same phase before they are connected together.***

If AC generators are not precisely synchronised before being connected to a network one will effectively present a “short circuit” to the other. Loss of ***synchronisation*** will severely damage both the generators and the network. Think.. sparks flying, flames, lots of smoke, damaged equipment, blown fuses. All those nasty and expensive things!

Whilst today’s AC networks are quite good at transmitting large amounts of electricity over very long distances, they are really *very lousy and complicated when we want to connect multiple generators to the same network at the same time.* Especially if said generators are separated by long distances.

POWER CONVERTER HISTORY

By the end of the 20th Century, more than 70 years or so since Tesla's AC network invention, the accepted way of converting AC power to a higher or lower voltage had always been through *use of transformers.* These always *worked at the same frequency as the power network*.

However 50Hz AC transformers are *very heavy, bulky and expensive to make*. In more recent times however, a new power converter technology has evolved. New high speed, solid state, very efficient MOSFET switches are now capable of *replacing Edison's old commutators.* DC as a *distribution system* is now back in style!

Back in the 1990s, "Switch mode" converters were first used in computers to provide high power in a small space. This technology has continued to evolve so that today, it can now *replace most conventional transformers.*

Modern power converters work by using diodes to rectify AC in to DC, just like Edison's commutators used to. They then "invert" this DC back in to *very high frequency AC*, typically well over 20,000Hz. This means the *transformer* used to convert the voltage is *much smaller,* more efficient and made with cheaper and lighter materials. We can now easily convert power back in to DC again at a higher or lower voltage or create a new AC from it by using special filters. Modern "grid connect" solar inverters operate on the same principle except that their input from the solar panels or batteries is already DC.

A "grid tie" solar inverter synchronises with the 50Hz AC power network and then converts the DC from solar cells or batteries to AC.

You don't need to know all that. All you need to know is that thanks to modern 21st Century technology we now have a cheap, efficient and reliable way to *convert AC or DC power* which both Edison and Tesla could only have dreamt of.

Converter technology means our existing power networks are now a bit of an anachronism. They were originally designed as a 50Hz AC network, because this permitted the use of transformers.

However now, we no longer need those transformers.

A high voltage DC converter. Thomas Edison would have just loved to have access to technology like this!

MODERN NETWORK PROBLEMS :

EXPLAINING NETWORK STABILITY

In all fairness, if we built a "green field" city today from the ground up, using the latest technology and with no need for compatibility with legacy systems of the past, the favoured power network would *probably be a DC one,* just like Edison's Menlo Park installation more than 120 years ago.

Modern power converters could be used wherever it was necessary to change frequency, voltage or current. Generators both small or large could be easily connected to the network anywhere, with **no need to synchronise**. We would have no need to worry about *"network stability". Thousands of small generators could easily take the place of one large one.*

Battery banks could be directly connected to the network anywhere, charging up when surplus power is generated and then discharging when there isn't enough power to go around. *Two wires could do it all.*

Alas both Rome and the rest of the world wasn't built in a day. All of our huge power networks today are low frequency AC. These have a topology designed to deliver *AC power* to millions of premises and consumers big and small, all from very big generators a long way away. A customer network where billions of electrical devices are in use daily, ranging from "brand new" to over sixty years old.

Over the last ten years or so, an increasing number of "micro generators" such as rooftop solar and small scale wind have been *connected to the* ***demand end of the network*** using line synchronising AC inverters. An AC network which was ***never designed for power to be injected from the customers' side.***

Once connected, these micro generators and inverters first "**synchronise" with the 50Hz AC that they already sense on the line.** Only then do they start "pushing." It's a bit like tapping your foot to your favourite song on the radio. The inverters then *continue to monitor the line frequency.* If it falters ever so slightly, the *inverter instantly disconnects in order to protect itself.* In effect these "micro generators" are all *slaves*, following the "big generator." This machine at the supply end of the line is **so big** that it will remain connected *no matter what happens to the network. It must remain locked at exactly 50Hz* and keep pushing, while all the little ones follow it.

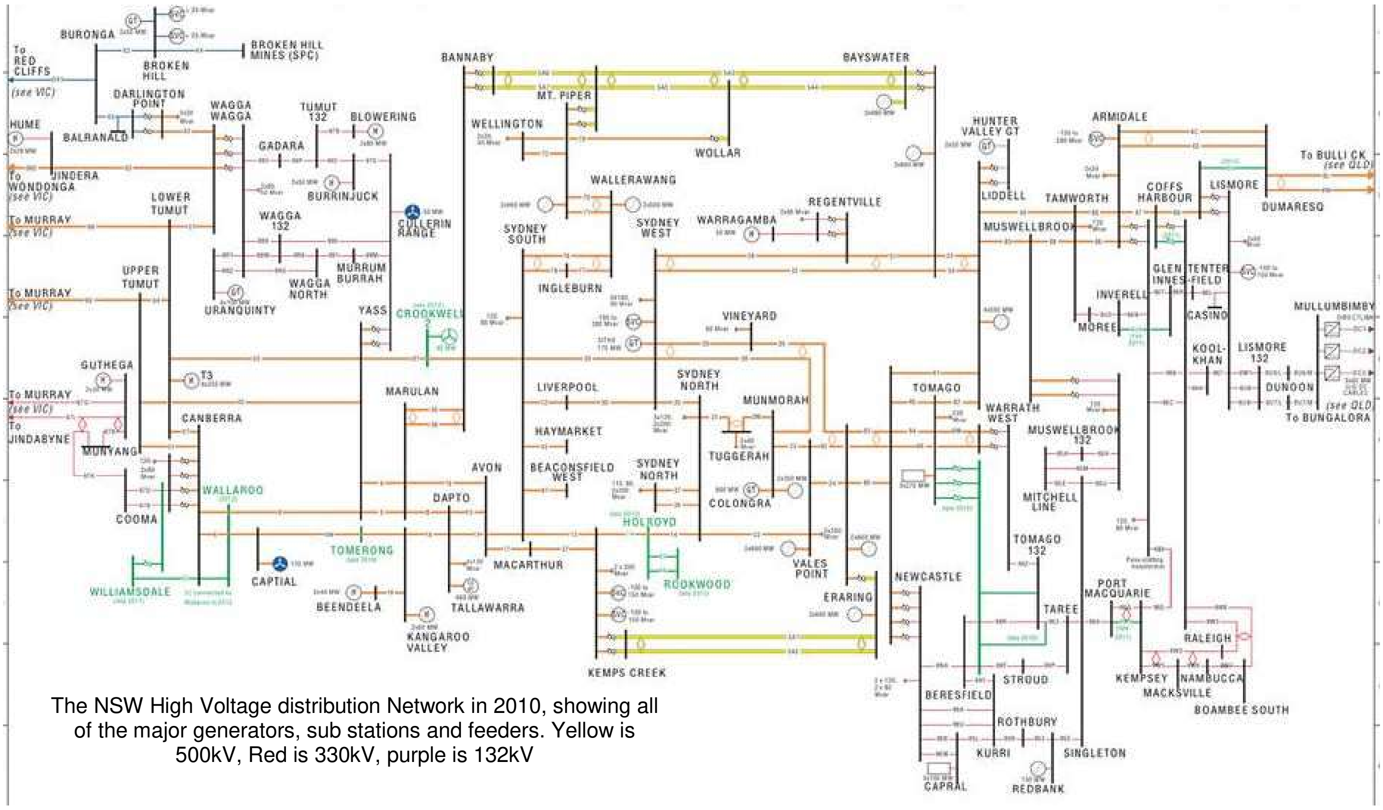
This "I'm the big boss so follow me" aspect of AC power networks is why the **largest generators in the network are the most important**. They are usually 300Mw or larger and almost always found in coal or nuclear power plants. These large generators must be big enough to be able to **start the entire network from cold** if it were to ever stop—without slowing down or changing frequency.

ROOFTOP SOLAR

Even if we have 2000 Megawatts of rooftop solar spread across 200,000 rooftops all over the state, if the whole network were to "go cold" (i.e. become unstable and lose power), none of them would *have anywhere near enough capacity on their own to be able to re start the entire network*, consisting of tens of thousands of huge transformers and millions of kilometres of cable. This is what they mean when they talk about **"base load".** It's the amount of dispatchable, frequency locked power that we need **on tap**, to be able to *re start the network from cold.*

This concept remains the same for *all small generators* in an AC network. Even medium sized gas fired plants and certainly all wind powered plants. Even hydro plants can create a challenge when using them to re start a cold network, especially if the hydro scheme itself consists of a large number of smaller machines.

In an AC power network, frequency is everything. Any generator not keeping up with the network will find itself out of synchronism and liable to damage if it doesn't disconnect immediately. That's how today's enormous, interconnected AC networks can so quickly go dark. *The more an AC network relies upon small generators to provide power, the **higher the risk that all those generators will disconnect** should network stability be lost due to one of the larger generators or transmission lines failing.*



The NSW High Voltage distribution Network in 2010, showing all of the major generators, sub stations and feeders. Yellow is 500kV, Red is 330kV, purple is 132kV

Small generators make the network more unstable because *they cannot be relied upon to immediately come on line and start pushing again to **correct frequency instability***. For example : Let's say a critical transmission line or 600MW generator trips and the system frequency momentarily drops by 0.1Hz as a result. At the same time, more than 2000MW of small rooftop solar generators will suddenly disconnect to save themselves. That means we suddenly *no longer have a 600MW network deficiency.. **We have a 2600MW one!***

This in turn creates *even greater frequency instability and the frequency drops even more*. As larger generators then disconnect to save themselves, the instability increases exponentially and almost instantly, *the entire network has gone dark.*

Now we've got a dark network which must be restarted. We can't *rely upon any of the smaller generators to help out*, because *they're all looking for 50Hz to synchronise with..* but they've got zero!

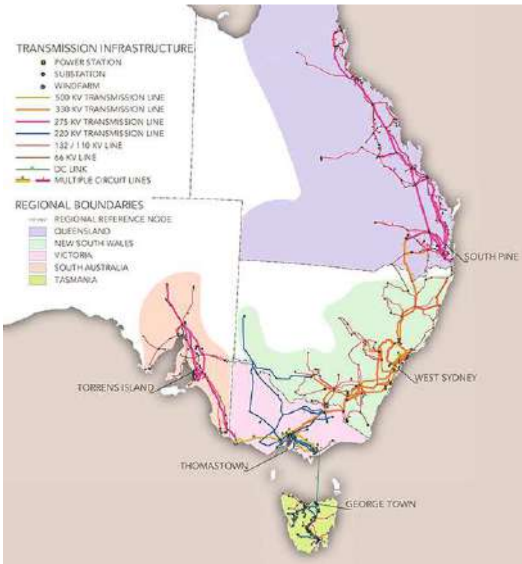
The procedure for restarting cold AC networks is complex and delicate. The highest energy parts of the network must be started first, using the largest machine available. Next, other large generators synchronise with this first one. They then then connect to the high voltage network and strengthen it enough to be able to withstand connection of some loads without risking a repeat of the disaster.

Once the 500kV / 330kV high voltage side of the network is restarted and synchronised with a few large machines on line and synchronised, the next voltage layer down (132kV) is started. Smaller generators then connect to this layer so they can then synchronise with the top layer. Next, it's the 66/33kV networks' turn. Finally, the 11kV consumer level loads and areas are progressively reconnected with a close eye on the network frequency meter with every load added. Once the consumer levels are all connected, the "consumer connected" micro generators and roof top solar can re synchronise and begin to push once again.

If the network relies too heavily on micro generators *connected at the consumer level*, it will become *impossible to restart the network.* *None of the small generators and substations at 11kV or below have enough capacity by themselves to restart the higher level transformers and levels.*

Regardless of the amount of small scale renewable generation we add to an existing AC network, we will always need very large machines connected at the high voltage end in order to ensure network stability. These machines must be dimensioned so that their *capacity* ***is high enough to restart all levels of the network*** without relying on small generators connected at the lower levels.

Transmission infrastructure on Australia's Eastern Seaboard. Note DC links to Tasmania and Queensland.



FUTURE CHANGES IN NETWORK TOPOLOGY

Until fairly recently, AC networks have always been extended and connected together using high voltage AC lines. However the modern approach is seeing an increasing number of high voltage DC interconnectors used. HVDC is a particularly good way of transmitting electricity across oceans, as the *sea itself can be used as one of the two conductors in the circuit.*

High voltage DC is now a reality thanks to electronic high voltage power converter technology. Edison would be drooling in his breakfast.

Already the Eastern Seaboard of Australia has HVDC interconnectors linking Queensland and Tasmania to the NSW / Victoria networks. The biggest advantage with HVDC, is that the ***frequency of the two interconnected networks no longer needs to be locked.*** A 500MW HVDC interconnector can be treated by one network as a *single large generator*, even though the energy supplying it may be *derived from many smaller ones*. Each side of the interconnector simply *synchronises with it's respective end of the network*, meaning the **two networks can be considered separate for the purpose of synchronisation.**

It is feasibly possible that in the distant future we may see gradual replacement of existing AC high voltage feeders with HVDC. This could divide our large AC networks into smaller ones, each requiring smaller "master machines" to maintain frequency lock. *HVDC feeders themselves can become the "largest machine",* permitting a greater number of smaller machines to be connected to the network without risking network stability.

Ultimately it is possible that the entire network right down to the 11kV level could one day be replaced with HVDC. This would eliminate the need to synchronise the network altogether and in effect make every local substation it's own network. In doing so, Edison's revenge upon Nikola Tesla would be complete.

What goes around, comes around and all that is old… is new again.

Paul Matthews—2019