# What Type of Power

## Alternating Current (AC) versus Direct Current (DC)

A great many books and articles have been written about the history of electric power generation. Some are New York City centric, as if no other place exists. Some are facility specific. Some are topical, such as the articles about 25 Hz electricity cited in this paper.

### *Direct Current (DC)*

The battle between advocates of Direct Current (DC) and the advocates of Alternating Current (AC) are well documented in the literature and the subject of TV documentaries. Therefore, this subject will be discussed only briefly here.

Thomas Edison was the main advocate of DC and considered AC to be extremely dangerous. He demonstrated that by dispensing many animals, including a rogue elephant, using AC. He also invented the “electric chair” to dispense rogue humans. The problems with and disadvantage of DC are the following:

> Power must be generated, distributed, and consumed at the same voltage, since there was no practical way change the voltage/current relationship.
>
> This made transmission and generator wires huge.
>
> Transmission was limited distances to the order of on city blocks or two miles, maximum.
>
> Neighborhood generating station were necessary, making DC power practical only in densely populated cities, such as lower Manhattan.

Consolidated Edison provided DC in New York City for 125 years, from 1982 to 2007.

It is noted that point-to-point, long, high-voltage DC transmission lines have been practical only in the past few decades, due to the use of high-power solid-state electronics.

### *Alternating Current (AC)*

The problem at Niagara Falls was that the first customers was in Buffalo, including the 1901 Pan-American Exhibition, 22 miles away. Not knowing what to do, it was even proposed that a pipe carrying compressed air be used to transmit power that distance. Transmitting electric power that far was challenging at the time. Once that challenge was conquered, the next challenge was to transmit electric power from Niagara Falls, Ontario to Toronto, a considerably greater distance.

Nicola Tesla, Charles Proteus Steinmetz, and George Westinghouse were the main advocates of AC. AC has the advantage that a simple transformer can be used to alter the voltage/current relationship at various points along the route. Therefore, the advantages of AC power are:

Power can be generated, distributed, and consumed at different voltages, since transformers can easily change the voltage/current relationship. Higher voltages are used for transmission and lower voltages for consumption.

Transmission, generator, and consumer wires can be different and more reasonable sizes, simply by using higher voltages to transmit higher power levels.

Transmission distances are no longer limited and can be many hundreds of miles.

Much larger regional generating stations are now possible.

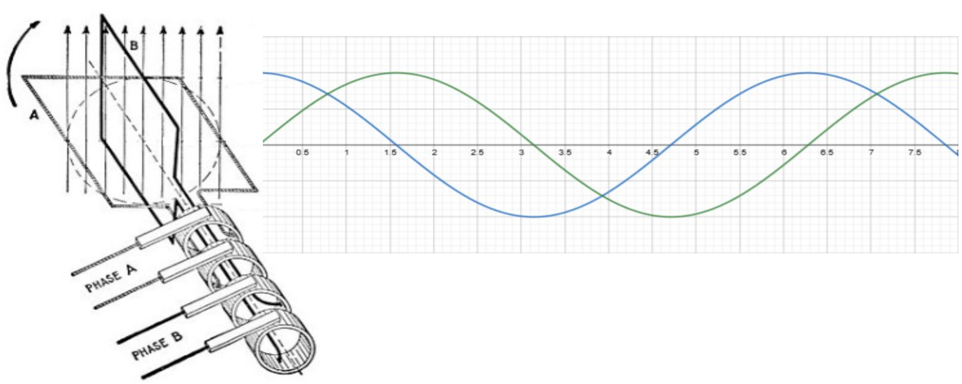
Today, the use of AC was the obviously correct choice. For example:

The Adams Power Plant generated power at 2,200 volts. Transformers then raised the voltage to 11,000 and later 22,000 volts for long distance transmission at lower current.

Robert Moses Power Plant generates power at about 13,200 volts and enormous current. It is immediately raised to 115,000 volts and much less current to transmission to the distribution facility. From there, power is supplied near and far at 115,000, 230,000, and 345,000 volts.

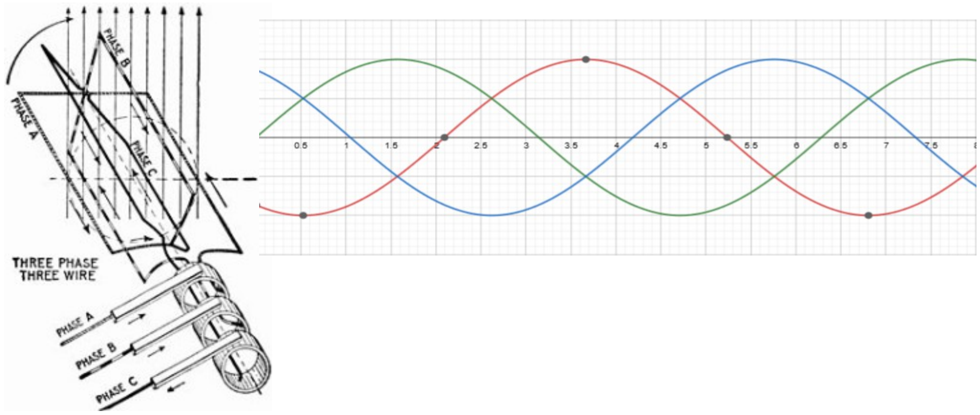
## Two-Phase Versus Three-Phase

At the time of this high pressure, “make it up as you go” project, the generators at the Adams Power Plant were built, using the only AC system the world understood, two-phase, four-wire AC. A two-phase generator has two outputs, that are 90 degrees, π/2 radians apart in phase from other, per Wikipedia and shown below.



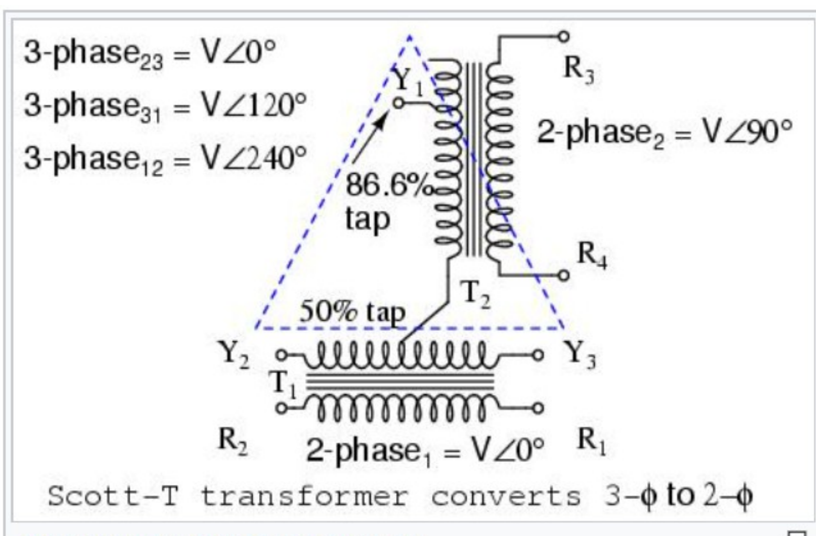

**Two-Phase, Four-Wire Generation and Waveform**

Charles Proteus Steinmetz pioneered the use of three-phase electricity in Europe. As Steinmetz and Nicola Tesla contemplated the problem of long distance power transmission, the concluded that a three-phase approach was superior. In three-phase power, the generator has three outputs, each 120 degrees, 2π/3 radians apart in phase from each other, per Wikipedia and shown below. Today, almost all power transmission systems are three-phase, a testament to Tesla's insight.




**Three-Phase, Three-Wire Generation and Waveform**

Next came the problem of how to interface the two-phase generators to Tesla's new three-phase transmission system. Wikipedia has a great description of the Scott-T Transformer configuration used for this purpose. See: [https://en.wikipedia.org/wiki/Scott-T_transformer](https://en.wikipedia.org/wiki/Scott-T_transformer). This configuration uses a bank of two transformers with specific winding ratios to convert between the two systems, as shown below from the Wikipedia article. The “T” in the name becomes obvious when the transformer windings are shown according to their vector orientation, as shown in the diagram. Winding R1-R2 is connected to one phase of the generator's output and winding R3-R4 is connected to the other phase of the generator's output. The three-phase transmission line is connected to the Y1-Y2-Y3 terminals. Although now shown, there can also be a “virtual neutral” tap, below Y1, which is useful for several purposes.



Standard Scott Connection 3 φ to 2 φ

**Scott-T Two-Phase to Three Phase Conversion Confiuration**

Once the power reached Buffalo, they didn't know what to do with three-phase power. So, they converted it back to two-phase, which seems downright silly today.

## Frequency

Prior the the existence of the power grid and inter-connectivity of generating facilities, power was generated at any frequency required by the local customer.

> Civil War era textile factories typically generated power at 40 Hz.
>
> Manhattan initially generated only DC power and did so until 2007.
>
> Switzerland still operates a 16.7 Hz nation-wide grid for its electric trains. (The trains can usually also operate on 50 Hz for trans-border use.)
>
> Power at Decew #1 in St. Catherines, Ont. Was initially generated at 66.66 Hz.
>
> Power at Niagara was initially generated at 0 Hz (DC), 25 HZ, 60 Hz and 115 Hz.
>
> Power at Niagara then standardized on 25 Hz, which was used by industry in both countries and used for residential power in Canada, but not the U.S..
>
> Power at Niagara was later generated at both 25 HZ and 60 Hz and now only 60 Hz.
>
> Europe and other parts of the world standardized on 50 Hz.
>
> North America and some parts of the world standardized on 60 Hz.

Gradually, frequencies settled on 25 Hz for the local grid. The IEEE Power & Energy Magazine articles cited in this paper provide a very complete history of the development of 25 Hz as the early standard at Niagara. This frequency is a compromise and related to the fact that the turbines for the Adams Power Plant had already settled on a speed of 250 rpm and power would have to be generated at some multiple of 8-1/3 Hz. 25 Hz was used extensively by industry in both Canada and the U.S. 25 Hz was also used domestically in Canada, but not the U.S. I remember my relatives in Saint Catherine's Ontario converting in the mid-1950s. Fort Erie Ontario was still on 25 Hz power at the time of the 1965 Northeast blackout.

After, 60 Hz electricity was introduced, both the 25 Hz and 60 Hz grids coexisted for well over 100 years 1895 to 2008. Although the grids were largely separate, interconnections were possible using rotary converters or frequency changers. Eventually, the remaining customers were transitioned and generators shut down or converted from 25 Hz to 60 Hz.

Each frequency has advantages and disadvantages. As an advantage, 25 Hz was best for slow-turning motors used in industry. As disadvantages, magnetic devices (motors, generators, and transformers) were much larger and heavier. Also, lights flickered annoyingly, as I remember from visiting my Canadian relatives in the early 1950s. The flickering would be much worse with modern fluorescent or LED lighting.

> John Dean Adams, John Birch Rankin, Toronto Power, Ontario Power, Schoellkopf 3-B, and Schoellkopf 3-C generated only 25 Hz power.

> Schoellkopf 3-A and Sir Adam Beck generated both 25 Hz and 60 Hz power.
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> Sir Adam Beck in Canada, the Huntley (steam) Generating Station in Tonawanda, N.N., and the repurposed (post-1940) John Dean Adams Transformer House had 60 Hz to 25 Hz frequency converters.

Power factor correction is also more problematic for 25 Hz systems than 60 Hz systems and much of the 25 Hz industrial load was inductive in nature. While 60 Hz power factor correction is easily accomplished using capacitors distributed throughout the system, 25 Hz power factor correction was more draconian and centralized. Harper Station in Niagara Falls, NY, had three “rotary capacitors,” which were “over-excited synchronous motors” without protruding shafts. They were large enough that maintenance was performed by entering the machine's enclosure, through a door-size hatch. After maintenance, the enclosure was sealed, evacuated, and filled to a pressure of 5 psi, 0.35 bar, requiring 14 cylinders of hydrogen gas. The hydrogen lubricated and cooled the machine and was, in turn, water cooled.

## *Moving power between the 25 Hz and 60 Hz grids*

While the 25 Hz and 60 Hz grids are completely separate, there are machines that can transfer power from one grid to the other. These would help balance the supply and demand aspects of the two grids. They are called “frequency changers” or, as the employees called them, “rotary converters.” These are interesting machines, as they must remain synchronous and in phase with two different power grids, operating at two different frequencies.

> Two 60-to-25 Hz machines were installed in the Adams Transformer House, after the transformers were scrapped, around 1940. A third was added in the 1960s. These were owned by Union Carbide, operated by Niagara Mohawk, and powered metallurgy furnaces in Niagara Falls, N.Y.. These machines were automatic and required an operator only to put them on-line and take them off-line.
>
> At lease one other 60-to-25 Hz machine existed at Sir Adam Beck #1.
>
> A  25-to-60 Hz also existed in Lockport, N.Y.

## *Changing the frequency generated by a generator*

As the needs of industry and availability of power changed, it was possible to change the frequency of the power generated by a generator from 25 Hz to 60 Hz or vice versa. To my knowledge, this was done in the U.S. only at Schoellkopf 3-A. It was also done in Canada at Sir Adam Beck.

> Gross adjustment: The winding/poles of the machine would be removed and replaced by a new and different number of windings/poles. The number of poles is determined by the frequency desired and the rotational speed for which the turbines were designed. The goal is to get as close to the desired frequency as possible, at the design speed.
>
> Fine adjustment: The speed of the turbine and generator would be altered to obtain the correct frequency. A different turbine, designed for the new rotational speed may also replace the old

turbine.

## Size Matters

Generator size is one of the most salient aspects of the rapid advance in the state of the art. Size information is difficult to obtain, inconsistent in terms of numerical value, units (horsepower versus kilowatts), and per-unit versus plant-total ratings. Also, the capacity of the generators could increase as much as 25% during the multi-year construction of a single generating plant. For example, the first generator installed may be 10,000 Hp and the last one installed may be 12,500 Hp. Nevertheless, the following table shows the rapid increase in per-unit generator capacity at Niagara as a function of time.

| Approximate Per-Unit Horsepower Ratings, etc. | | | | |
|---|---|---|---|---|
| **Year** | **Facility** | **Horsepower** | **Number of Machines** | **Frequency** |
| 1985 - 1905 | John Dean Adams | 5,000 | 20 | 25 Hz |
| 1905 | Rankine | 10,000 to 12,500 | 11 | 25 Hz |
| ~1910 | Toronto Power | 10,000 to 12,500 | 11 | 25 Hz |
| ~1910 | Ontario Power | 10,000 to 12,500 | 15 | 25 Hz |
| 1914 | Schoellkopf 3-A | 9,000 or 10,000 | 14 | Mixed |
| 1918 | Schoellkopf 3-B | 34,500 | 3 | 25 Hz |
| 1922 | Sir Adam Beck #1 * | 66,700 | 10 | Mixed |
| 1924 | Schoellkopf 3-C | 70,000 | 3 | 25 Hz |
| 1954 | Sir Adam Beck #2 * | 125,500 | 16 | |
| 1961 | Robert Moses | 240,000<br>(200 Megawatts) | 11<br>(1 in maintenance) | 60 Hz |
| Notes:<br>* indicates per-unit value, calculated from the published plant-total value<br>There is no longer any 25 Hz power generated in the region.<br>Sir Adam Beck #1 and #2 and Robert Moses are the only currently operating facilities.<br>1 hP = 0.746 KW , 1 KW = 1.36 Hp | | | | |

## References


- 25-Hz at Niagara Falls, end of an era on the Niagara Frontier, parts 1 & 2, IEEE power & energy magazine, January/February 2008
- Niagara Falls History of Power, http://www.niagarafrontier.com/power.html
- Rankine Generation Station, 100 Years of Power Generation, Professor Mark Csele, http://www.technology.niagarac.on.ca/people/mcsele/interest/rankine-generating-station/