The Electrical System as a Tandem Bicycle

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The system that delivers electricity to private citizens and companies across the country is highly complex. While electricity is an omnipresent and crucial part of our everyday economy, understanding this system and all its associated phenomena is not easy, sometimes even for trained electrical engineers. In such a case, a good analogy often helps to form a better idea of how things work. We have chosen to compare the electrical system with a tandem bicycle to explain a few of its aspects.

Of course, no analogy is a 100% perfect fit. The real electrical system and our imaginary bike system do not match on every count since all characteristics of the electrical system do not necessarily lend themselves to a translation into this bike system. Certain aspects of the analogy are not always completely accurate. However the similarities between the two are close enough to make the more easily visualized bike system of great help in understanding the more abstract electrical system. And that, of course, is the goal of this paper.

Acknowledgement

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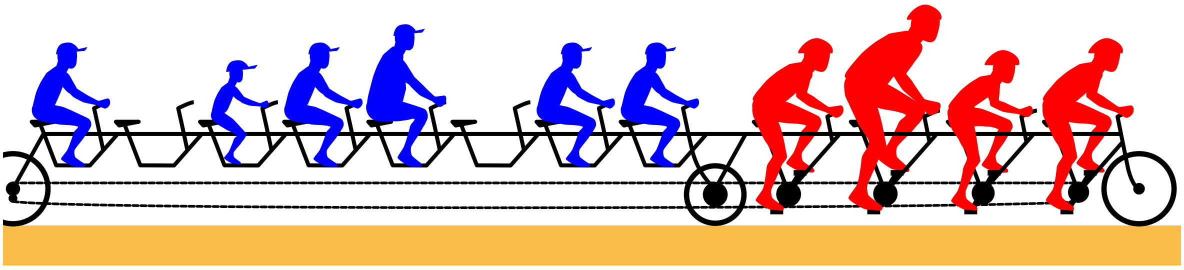
1 The basic representation of the system

Imagine a tandem bicycle moving at constant speed.



The goal of this whole system is to keep the figures in blue at the back of the bike moving, even though they are not generating any of the energy that keeps the bike in motion. They represent the load. There are large loads that consume a lot of electricity, industrial plants for instance, and smaller loads, like private dwellings.

The pedalling figures in red deliver the energy that keeps the system going. They are the power stations where electrical energy is generated. Some power stations are larger and stronger than others and thus supply more power.

The chain connecting all elements of the system is the equivalent of the electrical transmission network. That is the network of high voltage lines used to transport the electrical energy around the country. The chain must turn the wheels at a constant rate to maintain the same velocity. Likewise, the electrical network needs to have a fixed and constant frequency. The upper part of the chain should be under a constant physical tension, just as the connection in the electrical transmission network should have a fixed voltage level. The lower part of the chain is without tension and is the equivalent of the neutral wire in a transmission network.

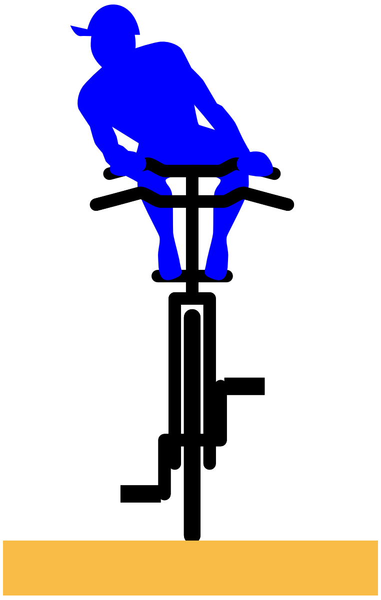
The pedalling movement (energy) of the red figures is transmitted to the chain by a gear or a gear system. This gear is like the transformer between the turning movement of the turbine in a power station and the electrical high voltage network.

Some of the red figures (= power stations) don't pedal at full power. They conserve some of their energy to be able to apply some extra force when needed to hold the same velocity. For example when another blue figure suddenly jumps onto the bike (= another load connects to the network), or one of the red figures gets a cramp and has to stop pedalling (= a power station experiences technical problems and has to shut down), replacement force is needed to maintain the same velocity.

The tandem bicycle analogy can also be applied to some of the specific characteristics of the Electrical Power System and its Power Quality as well.

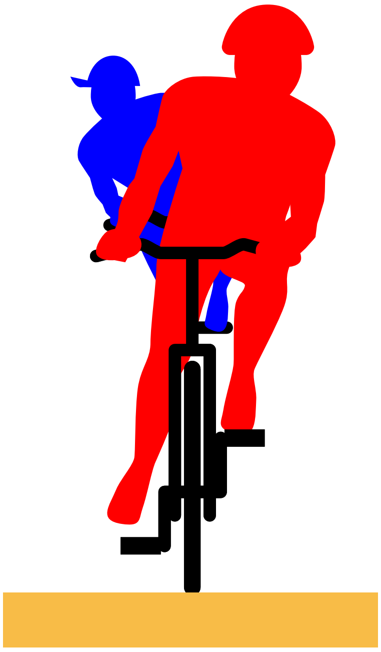
2 Inductive power and its compensation

An inductive load has a sinewave or reoccurring pattern with a normal frequency and voltage level, but is a bit delayed compared to the main sinewave on the grid. It originates in electrical motor induction coils, fluorescent lighting ballasts, and certain types of electrical heating.



Such an inductive load can be represented by a blue figure leaning to one side of the tandem (see drawing). It has the same weight (= normal load), so it doesn't influence the tension on the chain (= voltage level of the grid) nor the speed of the bike (= frequency of the grid), but without compensation it might cause the bike to fall over.

So a red figure needs to lean in the opposite direction to compensate (= a power station has to generate inductive power; power with the same delay in the sinewave as the load), see drawing.



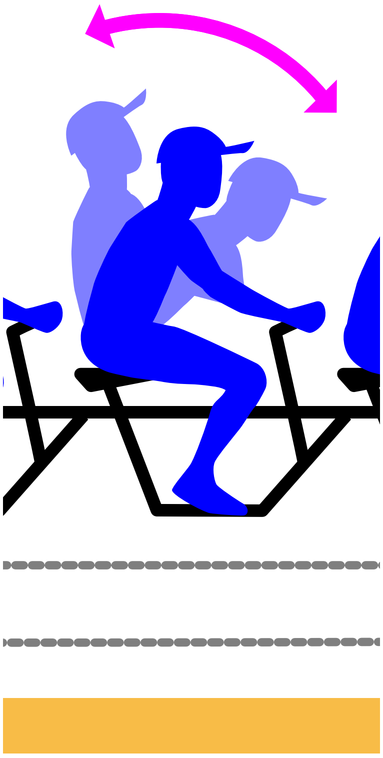
This has the following consequences:

- The compensation has to be immediate and exact or the whole bike (= electrical network) will fall over. This requires a clear understanding among the red figures doing the peddling (= among power stations) of what must be done, and the capability to react very quickly.
- A red pedaling figure (= power stations) leaning to the side can't work as comfortably as before. As a consequence, they will put less force on the pedals (= power stations will generate less 'active energy'; energy without delay on the sinewave). So the other red pedallers (= power stations) will need to add some extra force.
- With a blue figure, riding in the back and leaning to one side of the bike and a red figure leaning to the other, the bike catches more head wind, leading to extra losses. This is just like the inductive current flowing through the electrical grid; it brings about extra losses.

To counter these consequences, large inductive loads are in general compensated close to their source. This is done by a capacitive load, more specifically by a battery of capacitors. They have a current with a sinewave that has a certain lead time compared to the main sinewave of the grid. In this way, it compensates for the delay of the inductive load. A capacitive load can be seen as another blue figure sitting close to the first one but leaning to the opposite side.

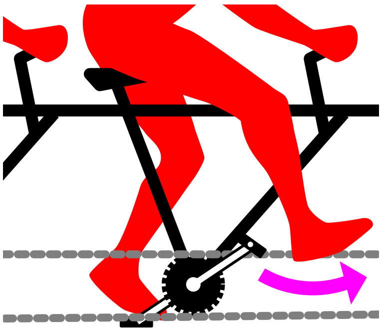
Inductive or capacitive loads are also called reactive loads. A load without a delay or lead time is called an active load.

3 Harmonic distortion



Imagine a hyperactive blue rider that is constantly bending forward and backwards (see figure). If he made this movement at the rhythm of the bike, it would do no harm. But a problem occurs if he moves three or even five times faster. This represents a harmonic load, a load with a frequency at a multiple of the normal frequency. TV sets, computers, compact fluorescent lamps, and electrical motors with inverter drives are typical examples of applications that can cause harmonic currents. Ideally these should be compensated for by harmonic filters close to the source; otherwise the bike starts to jerk forward and backwards, resulting in extra energy losses. Such a harmonic filter can be seen as a saddle mounted on castors that moves forward and backwards and in this way immediately neutralizes the movement of the hyperactive blue rider.

4 Keeping constant voltage and frequency



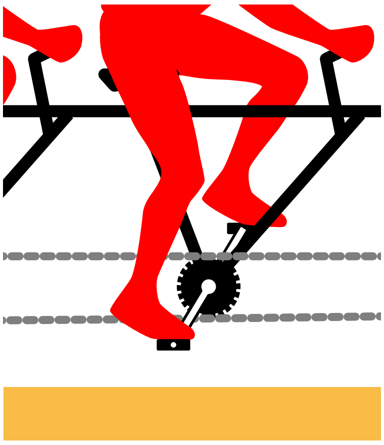
One of the red pedallers wears shoes that are too slippery. All of a sudden his foot slips off the pedal. Suddenly his contribution to the power of the system is lost and the tension on the chain drops. This needs to be compensated for by the other red pedallers to maintain the same velocity. The biker who slipped off the pedals has to be careful not to hurt himself, since the chain and his pedals keep on turning. It is a tricky operation to put his foot on the pedal and start doing his share of the work again with his colleagues.

This situation can be compared with a voltage dip. Due to a failure in a power station (= slippery shoes), it might happen that its control system suddenly shuts it down (= slipping off the pedal), but with the risk of damaging certain pieces of equipment since the network is more powerful and keeps the same frequency (= the pedal keeps on turning). The result of this drop out is a sudden voltage dip on the grid (= drop of tension on the chain) that lasts until the other power stations in the network react by raising their contribution. If they don't react fast enough, the frequency (= speed of the bike) might start dropping. And just like the pedaller who lost his pedal and finds it difficult to put his foot on the turning pedal again, it is a tricky operation for a power station to reconnect its generator to the network again, since the frequencies have to match.

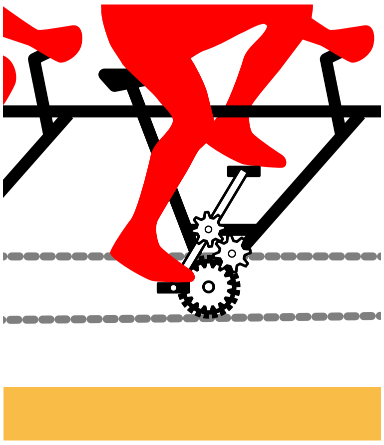
A similar voltage dip might happen when a heavy load is suddenly connected to the network. This is why most of the time heavy loads are not connected all at once but rather in incremental steps.

When a heavy load is suddenly disconnected, a voltage peak can occur. In such a case, the power stations have to lower their contribution quickly or the frequency will rise. In our tandem analogy, the bike will suddenly accelerate if any of the blue riders jump off the bike and the red pedallers continue to apply put the same force on the pedals. They have to react quickly and lower their power or the bike will start to accelerate.

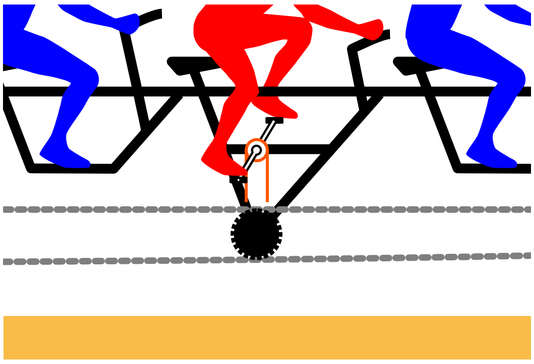
5 Three different types of power stations



If a red pedaling figure is directly connected to the chain with one gear, he has to constantly pedal at the right speed and with the right amount of power. This is the case for large traditional power stations and nuclear power stations which are connected to the grid by a transformer.



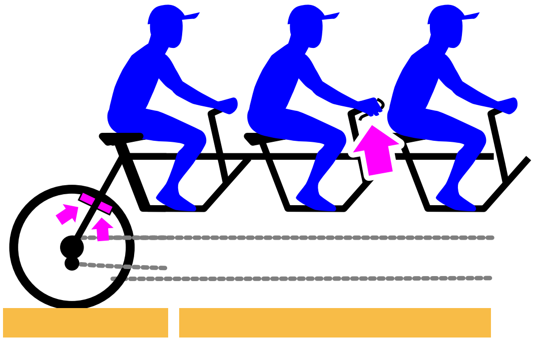
Some bikers can pedal slower however, since their force is transformed to the right speed by a gear system. That corresponds to power stations that run slower, for instance a hydro power station whose turbine speed depends upon the flow of the river. In such a case, the turbine is connected to the generator just as in the case of the tandem bike by a gear system that transforms the speed. Another option is that the generator turns at the same speed of the turbine and the right frequency for the grid is reached by a frequency inverter.



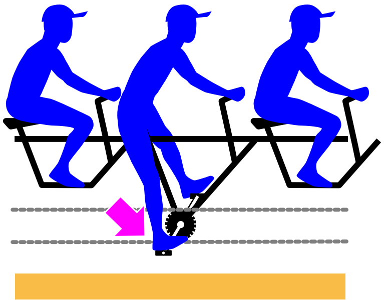
Wind turbines are like small red figures who pedal only when the weather is fine. The nicer the weather, the faster they pedal. They are of great help sometimes, but you cant rely on them. This is the same as wind turbines: they only function when the wind speed is not too slow and not too fast. This is why they need to be backed up by other types of power stations. These fair weather pedallers are connected to the chain by a belt and a gear system, allowing them to pedal at varying speed, in the same manner wind turbines are connected by a gear box or by a frequency inverter to offset the variations in wind speed.

6 Three different types of loads

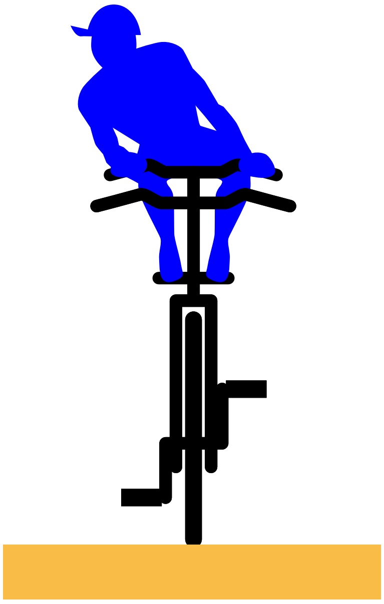
Not only do power stations differ a great deal in their characteristics, the loads differ as well.



A first type of electrical load is a resistance, producing heat or light out of the electrical energy. Examples are the light bulb or most types of electrical heating systems. It is the equivalent of a blue rider without pedals, but continuously pulling on the brakes. Those brakes transform kinetic energy into heat in the same way an resistance transforms electrical energy into heat.



An electrical motor has a basic principle that is similar to a generator. But instead of transforming rotating energy into electrical energy, the motor transforms electrical energy back into rotating energy. In the analogy, this can be represented by a blue rider with his feet on the turning pedals just like the red figures (= power stations), but instead of pedalling along, applies his full weight against the rotating movement.



A third type of load is the reactive load, already discussed in point 2. This is the blue rider without brakes or pedals, leaning to one side. This creates an inductive load with a certain delay compared to the grid (a fluorescent lamp for example) or the opposite, a capacitive load with a certain lead compared to the grid (for example a battery of capacitors).

7 Conclusion

This analogy makes it clear just how complex it is to manage a power system. The power generated at any given moment must exactly compensate for the load. Maintaining this fragile equilibrium means controlling several dimensions. The most difficult challenge is that both the speed of the chain (frequency of the network) and the tension on the chain (voltage level) must remain steady. And all while different and unexpected disturbances of the equilibrium might occur.

Since the liberalization of the electricity market in Europe, each country has an independent network operator who strives to execute this task.

References

[Soeder, 2002] Lennart Soeder, Explaining Power System Operation to Non-engineers, IEEE Power Engineering, April 2002