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Explaining Power System Operation to Nonengineers

Using an analogy with a tandem bicycle may help people visualize and understand basic power system phenomena

It is sometimes difficult to explain how a power system works, especially for people who have not studied electrical engineering. This article shows how the interactions of a power system and its components can be explained using the parallel with a tandem bicycle. The active power balance in the power system is modeled by the parallel of keeping a constant speed of the bike, while the reactive power balance is represented with the fact that the bike has to be kept on the road without overturning.

Consider a long tandem bicycle. The bike is made of flexible material, and the chains between the different sprockets under the different cyclists are slightly elastic. When the bike is standing still, all the pedals on one side of the bike will be at exactly the same position, e.g., at the bottom position. Assume also that the bike is run on a flat, straight road, and the aim is to keep a constant speed of the bike and the bike should be kept in an upright position. The wheel losses and air resistance are neglected.

Many functions in the power system can be illustrated with the mechanical parallel of a tandem bike that is kept running at a constant speed (constant frequency) and in an upright position (voltages at 1 pu). The parallel gives a good visualization of phenomena such as active power balance, frequency control, asynchronous machine slip, reactive power balance, and voltage control.

Active Power Balance

On the bike, there are cyclists (generators) who pedal continuously, but different cyclists pedal with different force. Since all sprockets are connected with chains, this implies that they rotate at the same speed. A so-called "bike rpm" (system frequency) related to the speed of the bike is obtained. There are also some people sitting on the bike, and they are just braking (loads) all the time. Some of these people try to stop their pedals (motor loads). It is now important to note that the sprockets connected to these pedals also have the same "bike rpm." To keep a constant speed of the bike means that the total force of the cyclists (total generation) has to be exactly the same as the total braking power of all braking people (total load).

Synchronous Machines

Some cyclists, so-called "synchronous" cyclists, have their pedals connected directly to the sprockets. This is the most common way of connection between pedals and sprockets for the grown-up cyclists (large power plants). This implies that all "synchronous" cyclists will bike with the same speed. It must, though, be noted that the chains between the cyclists are slightly elastic. This means that there will be an angle difference between the different cyclists, i.e., the pedals will not be at exactly the bottom position at the same time. It can be noted that some cyclists (hydro power stations) perhaps prefer to bike slower. Then they must have a gear (several machine poles) between the pedals and the sprocket. It can be noted that a sudden change of

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the force on the pedals causes some oscillations (angle dynamics), since there is some inertia in the sprocket connected to the pedals and the chains to neighboring sprockets are elastic.

Asynchronous Machines

Some cyclists, normally children (low power production) who cannot bike so much, prefer to use a softer connection between the pedals and the sprocket. They use instead a belt, which implies that they, depending on the belt slip, have to bike slightly faster than the bike rpm. These cyclists are called "asynchronous" cyclists.

Loads

Some cyclists, who always have toe clips, try to stop the bike by using the pedals. This type of cyclist often uses the belt between the pedals and the sprocket (asynchronous motor loads). Since they try to brake the bike, this implies that their pedals will rotate slightly slower than the bike rpm. There are also other types of persons on the bike that use brakes directly connected to the wheels (impedance loads).

Frequency Control

Some of the synchronous cyclists continuously look at the speed of the bike (frequency control). If the speed decreases, depending on an unreliable cyclist (unit outage) or too many braking cyclists (load increase), then these "speed controllers" adjust their stroke on the pedals in order to adjust the speed. They always have to keep a margin so, if too much happens with the speed, then they shout to some other cyclists to change their effort. On some bikes (deregulated) a special person, who is not biking and who is responsible for the speed control (independent system operator), asks the one that is prepared do it for least cost (cheapest bid on regulating market) to change his or her pedal stroke.

Wind Power

Some cyclists only pedal when it is windy. Often they use the belt between their pedals and the sprocket, which means that they pedal slightly faster than the bike rpm. They are still rather strongly connected to the sprocket rpm, which means that their own rpm is nearly constant, independent of the wind speed. It can be noted that some wind-controlled cyclists use a kind of gear (double-feed asynchronous generator) that makes it possible to pedal slower at low winds and faster at high wind speeds. When the wind speed lulls, these cyclists will put less force on their pedals. But still, the rpm is about the same. The consequence is that the bike runs a bit slower, and the "bike speed controllers" increase their force on the pedals. This is from the bike's point of view exactly the same as what happens when some cyclists increase their braking force. It can be mentioned that on some bikes (like the Swedish deregulated system) it is possible for some braking cyclists to have a deal with the wind-controlled cyclists. The deal is that the wind-controlled cyclists should pedal as much per year as the braking cyclists brake per year, measured as energy. The consequence is that sometimes the wind-controlled cyclist pedals much more than the braking cyclist brakes. The consequence is that some other cyclist on the bike can pedal a little less and store their oil or water. This oil and water can be stored to another occasion when the wind-controlled cyclist bikes less than its counterpart brakes. Remember that it is still the "speed controller" that makes the bike run with the same speed (i.e., keeps the balance between production and consumption).

Reactive Power Balance

A problem on the bike is that the seats of some cyclists and braking people are not positioned on the midpoint of the bike. The consequence is that the bike will overturn (voltage collapse) if these forces are not balanced. Figure 1 shows how a four-person tandem bike can look from above.

For P_G, the cyclists try to accelerate the bike, while for P_D, the braking cyclists try to decrease the speed. Q_L are forces that try to overturn the bike to the left, while Q_R tries to overturn it to the right. The aim is to keep the bike in an exact vertical position (voltages = 1 pu), but a slight angle difference from vertical is still acceptable (slight voltage deviation from nominal).

Asynchronous Machines

The asynchronous cyclists, the ones with the belt, always sit a bit to the right of the bike midpoint. This implies that this causes a force on the bike (they consume reactive power) that overturns it to the right if this force is not compensated. It does not matter if they pedal (asynchronous generators) or if they brake (asynchronous motors).

Capacitors

There are some special high capacity people who never bike or brake. They just sit on a seat, located on the left side of the midpoint of the bike (capacitors produce reactive power). The best location is to have them close to asynchronous cyclists in order to compensate them directly. If the capacitors are located in another position on the bike, then extra forces will be induced on the bike frame.

Synchronous Machines

The synchronous cyclists have seats that could move from the right side of the midpoint (reactive power consumption) to the left side (reactive power production). By studying the balance of the bike, they move from left to right in order to keep the bike in an upright position (control of reactive power to keep an acceptable voltage). It can be noted that the possibility to move from left to right is limited by the force on the pedals. When they pedal a lot, they cannot move so much from left to right (total current limits reactive power production/consumption at high active power production).

An Example

The forces on the four-person tandem bike in Figure 1 are shown in Figure 2.

Person 1 is a synchronous biker who is in charge of keeping the bike on the bike rpm, P_{G1} and also keep the bike in an upright position, Q_{L1} (a synchronous machine with frequency and voltage control).

Person 2 tries to stop the bike by trying to pedal in the reverse direction, P_{D2}. The pedals are connected with a chain to the

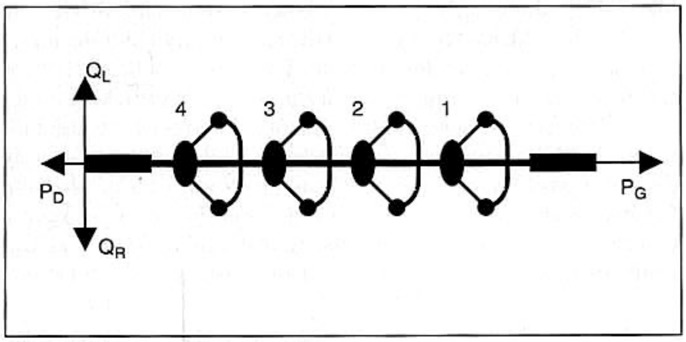

Figure 1. Forces on the tandem bike

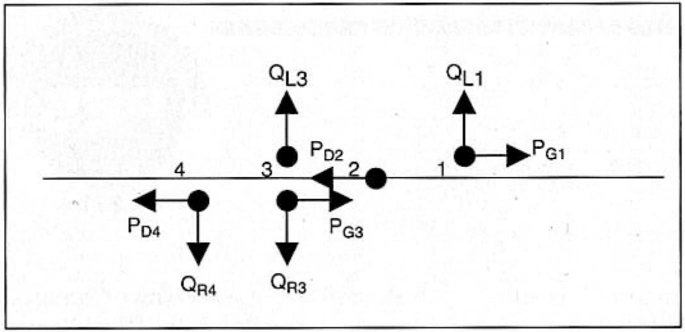

Figure 2. Forces on a four-person tandem bike

sprocket (a synchronous machine). The seat is fixed on the midpoint of the bike, i.e., $Q_{L2} = Q_{R2} = 0$, (only active consumption, no reactive production, nor consumption).

Person 3 is a wind dependent cyclist, P_{G3}, who uses a belt between the pedals and the sprocket. The seat is positioned a bit to the right of the midpoint of the bike, Q_{R3} (an asynchronous generator). In order to compensate for the wrong position of the seat, there is another, nonbiking person just sitting on the other side of the midpoint on another seat, Q_{L3} (capacitors for power factor correction).

Person 4 tries to stop the bike using the pedals, P_{D4}, which are connected to the sprocket with a belt. The seat is positioned a bit to the right of the midpoint of the bike, Q_{R4} (an asynchronous motor).

The bike controller is person 1, which means that the forces of this person have to be controlled to:

$$P_{G1} = P_{D4} + P_{D2} - P_{G3}$$

to keep a constant bike rpm, and

$$Q_{L1} = Q_{R4} + Q_{R3} - Q_{L3}$$

to keep the bike in an upright position.

The overturn forces, Q, are not balanced in the same point, and the frame is not rigid. This means that the bike will lean slightly to the right at point 4 (voltage < 1 pu) and slightly to the left at points 1-2 (voltage > 1 pu).

Limitations of the Model

Many phenomena in the power system can be illustrated with the tandem bike parallel. There are, though, some parts that I, so far, have not succeeded to represent in a natural way. One example is active power line losses. It can be mentioned that the total strain on the bike frame between cyclist 3 and 4 in Figure 2 depends both on transmitted forward force, P, and overturn forces, Q (current load).