The role of “generator inertia” in the electric power generating system

Douglas A. Kerr

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ABSTRACT

In each of the four distinct “power grids” (formally, “interconnections”) serving the United States and Canada, most of the electrical power has traditionally come from turbine-driven synchronous alternators (generators). These are inherently interlocked to operate at precisely the same frequency (the frequency of the grid), and all regulate their operation to deliver their appropriate quota of power into the grid while operating at such a speed that this frequency is as intended (60.0 Hz).

If a major power station on the grid unexpectedly has to suddenly stop operation, its contribution must now be picked up by the other participants. But the nature of turbine-driven alternators is such that they cannot do this “instantaneously”. The result is that, for a short period, the speeds of the alternators (and thus the frequency of the grid) will “dip”, not an ideal situation.

But mitigating the slow response of the turbine-driven alternators is the fact that each one stores, in its spinning rotor, a substantial amount of energy in mechanical kinetic (“inertial”) form.

This energy is inherently and immediately contributed to the grid (at every such power station) without any action required on the part of the control systems. As a result, the “grid frequency dip” that might otherwise occur is significantly reduced.

Today, though, a substantial part of the power generated in each of these grids comes from photovoltaic (solar) systems. They differs in two ways (with respect to the topic of this article) from traditional turbine-driven alternator systems. Firstly, they can almost instantaneously increase their output power (up to the maximum possible at the moment) when needed in the event of loss of capacity elsewhere. That is a positive for such systems.

But they do not have an equivalent of the “inertial energy” held by traditional turbine-driven alternator systems. Thus they cannot briefly “punch above their weight” to cope with the dynamics of loss of another major source—a negative for such systems. Thus the planning

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of the configuration and management of power grids has be done under a new set of realities.

1 SYNCHRONOUS GENERATORS

1.1 Introduction

For many years, the electrical power generating “system” of the United States and Canada revolved (to make a bad pun) around turbine driven synchronous alternators,. which are of course “rotating machines”. The turbines referred to might be driven by steam, directly by gas combustion, or by water. Although there are important technical differences between the three classes, for our purposes here it is not necessary to look into those.

“Synchronous” here means that the frequency of the alternator’s output is precisely related to the rotational speed of the alternator. The relationship depends on the number of poles of the alternator’s structure.

1.2 An isolated alternator

Consider now a large factory whose power comes exclusively from an on-site power plant equipped with one steam turbine driven synchronous alternator. There is no connection of any sort between this complex and the “power grid”.

Assume that the power load from the factory is small but steady as the start of the work day approaches. The speed-regulating system of the alternator[1] has manipulated the ”throttle” of the steam turbine so that the turbine turns the alternator at the speed needed to produce the “assigned” output frequency (assume 60 Hz) within some small tolerance. The field current of the alternator has been adjusted so that its output voltage is that desired.

Now, at the start of the work day, the whistle blows (ah, how nice to have steam for that from the power plant’s boiler), and hundreds of machines are started within a few seconds. The load on the alternator suddenly and dramatically increases.

The immediate effect is that the torque required to turn the alternator has increased significantly, and this in turn causes the turbine to slow down. One result is that the output frequency of the alternator decreases.

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[1] At one time a “flyball” mechanical governor, but today an electronics-based system.

The speed-regulating system of the machine senses this and opens the steam throttle further, in order to increase the torque developed by the turbine and thus bring the rotational speed of the machine back to that required to produce the assigned output frequency. But the turbine cannot increase its torque instantaneously, and so output frequency decline further, and this lasts a few seconds, not a desirable situation.

However, there is a consideration, not previously mentioned, that mitigates this phenomenon. The turbine and alternator rotors (directly coupled—from here on I will refer to them collectively as **the** rotor) have a substantial *moment of inertia*. One implication of this is that when the machine is rotating, the rotor stores a substantial amount of mechanical kinetic energy. It is said that this gives the machine a substantial amount of "inertia".

The traditional concept of inertia is that it makes bodies at rest "tend to stay at rest" and makes bodies in motion "tend to remain in motion.[2] In particular, the latter tendency comes from the fact that, if the body in motion were to somehow "wish" to slow down, part of the stored kinetic energy would come into play to "keep it moving" at (approximately) its original speed.

When we have the sudden increase in load I postulated, this inertia helps to keep the machine to continue turning at near its original rotational speed (while we wait for the turbine to increase its torque. In effect, the inertia slows down the "slowing down" phenomenon.

It is in fact this is the "inertia" phenomenon that is the central topic of this article.

2 INTERCONNECTION

2.1 Introduction

But our real topic here is not this hypothetical isolated factory and its power plant and, but rather the modern electrical supply "grid".

The preponderance of power generating stations of The United States and Canada are "interconnected" in one of four "interconnections" (to use their formal names), with basically geographically-defined realms, as shown in this figure:

[2] This applies to rotational motion as well as the linear motion most often envisioned.

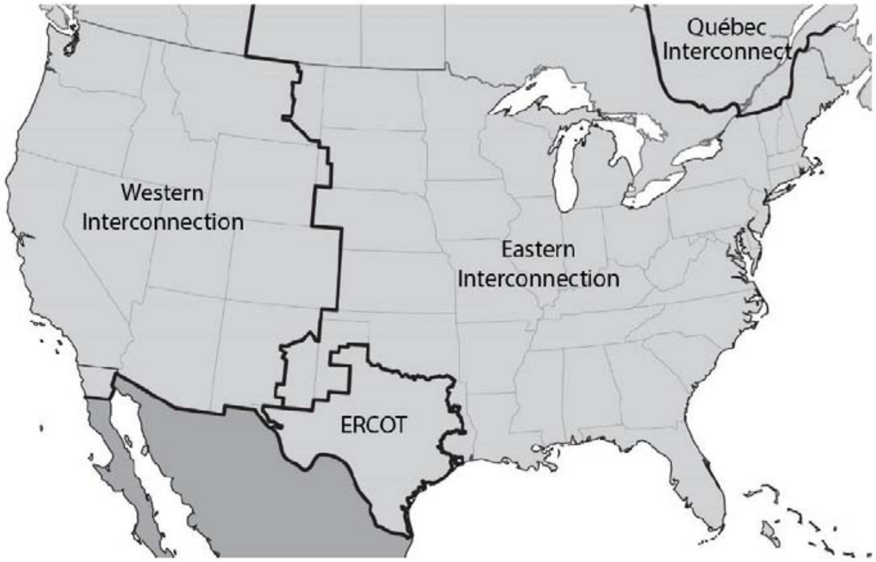


Figure by NREL (see Section 8)

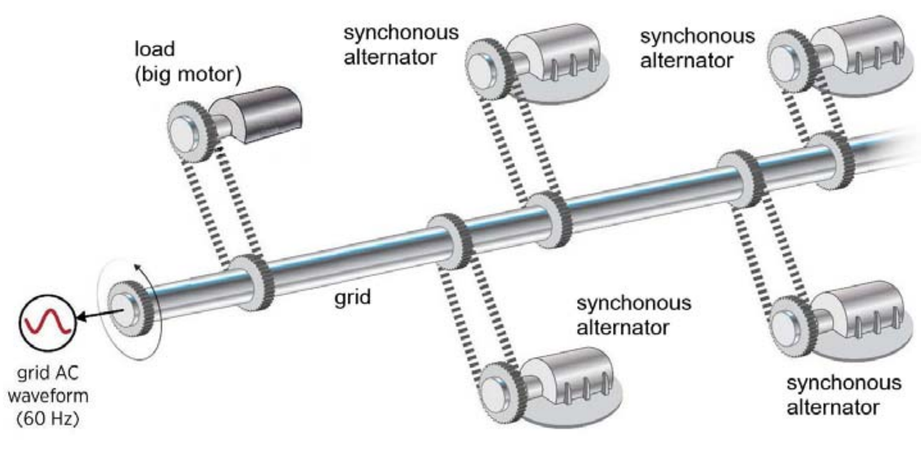
Figure 1. Interconnections of the US/Canadian power system

ERCOT refers to the interconnection operated by the Electric Reliability Council of Texas

> As an editorial note, I will from here on generally use the term "grid" rather than "interconnection" for these "networks". "Grid" is in popular use with essentially this meaning, and "interconnection" has other, possibly conflicting ,meanings.

In each grid, all the synchronous alternators operating at all the power generating stations are essentially electrically connected in parallel. That in means that, like it or not, all the operating synchronous alternators are rotating at precisely the same speed.

The concept is illustrated by this mechanical metaphor:



Adapted by the author from a figure by NREL (see Section 8)

Figure 2. Grid metaphor

The grid (in reality an electric bus) is represented here by a shaft. All the synchronous generators are connected to it by toothed belts, so they all perforce turn at exactly the same speed.

The overall load on the grid is represented here by a single fanciful "big motor".[3]

For each alternator, part of the control system manipulates the alternator field current so that the amount of power sent by that alternator into the grid is proper, perhaps the most that the alternator is rated to produce on a continuous basis, or perhaps some lesser value based on the today-complex provisions of the contracts by which electrical energy is bought and sold among multiple entities.

2.1 Inter-grid ties

Note that none of these four grids are directly tied to another, such that they both would at any instant have precisely the same frequency.

But there may well be "ties" between grids allowing energy to pass from one to the other, in order to execute the complex arrangements for dealing with shifting loads and shifting generating capabilities, and the associated buying and selling of energy.

These ties involve power converters, conceptually similar to those I will discuss later (Section 4) in connection with solar generation. They in effect push power into the "recipient" grid at the frequency at which it is presently operating.

2.2 Frequency control

Note that no single alternator, nor even the multiple alternators at a large power station, can significantly affect the frequency at which the grid operates. That is a function of the collective operation of all the thousands of alternators feeding that grid.

Nonetheless, at each power station, for each alternator, its own control system manipulates the turbine throttles based on the observation there of the grid frequency.

Thus, each alternator "thinks" it controls the grid frequency, and as a result, they collectively all do just that.

[3] It is shown as being connected by a toothed belt, suggesting it is a synchronous load, but that is an accident of how I adapted the illustration, and that inference should not be drawn.

3 A LOAD CHANGE EVENT

3.1 Sudden loss of output

Suppose that at a certain time an entire generating station on one of our grids must completely shut down quickly.

The result is that the load on the remaining stations (that is, on all the alternators at these stations) suddenly increases. As we heard earlier, the result is that the torque demand of each alternator on its driving turbine increases, and (given the present setting of the turbine throttles) the machines slow down. This of necessity happens at all the generating stations, and thus the grid frequency decreases.

3.2 Response

At each alternator on the grid, the initial reduction of grid frequency is noted, and the turbines ordered (by throttle manipulation) to increase their torque.

The result of this, not just at one alternator but at every alternator in the grid, is that in due time the operating speeds of all alternators come back up to that required to produce the standard frequency.

But, as mentioned earlier, the turbines by their nature cannot instantaneously increase their torque. As a result, there may be a significant “dip” in the grid frequency for a short while (several seconds).

3.3 Inertia to the rescue

However, as we heard earlier in connection with the single isolated alternator, this slowing of the machines until the turbines can “catch up” is itself slowed by benefit of the energy drawn from the kinetic energy stored in the machines’ rotors. Thus, the degree of frequency dip is less than it would otherwise be.

Note that only a small fraction of the stored mechanical energy is devoted to this sustaining of the alternator speed (within a small amount of change) during this event.

In fact, for a given moment of inertia of the machine rotor, the stored kinetic energy is proportional to the square of the rotational speed. That means that in an event such as I have been discussing, if, with the help of inertia, the decrease in the rotational speed of all the turbine alternators on that grid is limited to only about 1% of the initial frequency, only about 2% of the inertial energy will have been brought to bear on slowing that phenomenon.

Looking at it in the opposite direction, for the inertial energy to have a significant effect on resisting frequency dip during an “event”, the total inertial energy at operating speed must be huge.

Fortunately, the traditional construction of these high-capacity turbine alternator rotors is massive, and a quite large moment of inertia is attained without taking any special measures.

On the other hand, as designers consider new designs that might save considerable weight of the materials in the machine rotors, they may be cautioned that doing so could in fact be counterproductive.

4 SOLAR PANEL (PHOTOVOLTAIC) ARRAYS

4.1 Introduction

Today, a significant fraction of the energy delivered into any of the grids comes from large solar photovoltaic (PV) panel arrays, operated by various entities.

The photovoltaic panels generate electrical power in DC form. This is then changed by special DC-to-AC converters[4] into AC, which is then fed into the pertinent grid. These converters are programmed to “play the grid game”, in a sense making the installation, as a participant in the grid, behave like a power plant with turbine-driven alternators.

The converters in effect “push power at the frequency of the grid” up to the lesser of:

- The AC power that can be derived by the DC power that the PV panel array can deliver under the present solar irradiance (which varies with time of year, time of day, incidence of clouds, etc.).
- The limit that the inverter itself can deliver (which might be different on “short tem” and “long term” bases).
- Perhaps some other value dictated by contractual provisions.

4.2 Sudden loss of output

Again assume that there has been a sudden and substantial loss of output on the grid. Discussed earlier, the impact would have been a reduction in system frequency.

The reaction at the PV generating station would have been to contribute power to the system. Effectively, this makes it easier for

[4] These are generally referred to as “inverters”, but in the broader context of issue in this article, often as “power converters” (which is of course accurate).

the turbine-driven alternators to more readily raise their (all identical) speeds and restore the system frequency to the intended value.

4.3 Comparison with turbine-alternator stations

Compared to turbine-alternator generating stations, such a PV generating station:

- Can respond much more quickly in increasing its “push” when even a small frequency decline is sensed, assuming that this does not require exceeding its maximum output capability (a **plus** for the PV station)

- Does not have energy stored in the form of mechanical kinetic energy that it can instantaneously deliver to the system (even beyond its normal maximum output capability) during a frequency dip incident (a **minus** for the PV station).

5 WIND TURBINE GENERATING SYSTEMS

Today, a significant fraction of the energy delivered into any of the grids also comes from sets of wind turbine generators.

The actual generator turned by the wind turbine blades typically generates DC. The output of the generator is fed to a power converter, which converts it to AC form, synchronized with the grid frequency.

The overall operation proceeds in mach the same as described for photovoltaic generating systems in section 4, with one difference. When the turbine blades are turning, there is stored in the rotating blades (and the generator rotor) kinetic energy (just as in the case of the traditional synchronous alternators). But not all wind turbines systems are arranged to exploit this.

Imagine now a wind turbine that **is** arranged to exploit the stored kinetic energy in the rotating elements. With the turbine blades turning at a speed dependent on the present wind incidence, with a commensurate power being delivered by the generator, and there is a capacity loss incident on the grid (calling for all generating stations to increase their output), this wind turbine can almost immediately (albeit for only a short time) increase its output power by drawing upon that mechanical stored (“inertial”) energy. (That assumes that this greater power is not above what can be handled by the power converter, considering that it may occur for only a very short time.) This is, for that short time, more power than can be extracted from the wind under the current wind situation. The turbine generator, is, for a brief time, “punching above its weight”.

In reality, then, the behavior of a wind turbine generator of this type in the matter discussed here is between that of the traditional synchronous alternator system and that of the photovoltaic generating system.

6 SYSTEM-WIDE IMPLICATIONS

Until recently, the overall detailed strategy of managing grid systems had depended on the fact that the participants were all turbine-driven alternators. Thus it could be assumed that there was in the system, at any given time, a certain (and substantial) amount of energy stored in mechanical kinetic form, which could be **inherently**, **and without delay**, "donated" to the system during, for example, a loss of capacity incident.

Now, for a given overall, continuous output generating capacity on a system, there may well be a smaller amount of such stored "inertial" energy.

Yet, counterbalancing that, both photovoltaic and wind turbine systems, because of the capabilities of their power converters, can almost instantaneously increase the power they "push" into the grid (up to a certain limit.

Thus the overall dynamics of power grid operation have changed significantly from the "traditional" situation, requiring the planners and operators of power grids to adopt new premises for system design and operation.

That matter is beyond the scope of this article.

7 A REFERENCE

An excellent paper on this topic, thorough and detailed but not overly esoteric, is:

Denholm, Paul, Trieu Mai, Rick Wallace Kenyon, Ben Kroposki, and Mark O'Malley. 2020. Inertia and the Power Grid: A Guide Without the Spin. Golden, CO: National Renewable Energy Laboratory.

It is available here:

https://www.nrel.gov/docs/fy20osti/73856.pdf

8 ACKNOWLEDGEMENT

The illustration at Figure 1 above is taken from the paper cited just above. The illustration at Figure 2 above is adapted by this author from a figure in that paper. Many thanks to the authors and those who contributed these excellent graphics.

Those illustrations are used here by virtue of the fact that those publications were sponsored by the US Government and thus are in the public domain.

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