Efficient Use of Electrical Power in the Context of Sustainability

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This paper is based on an oral presentation made by Academician W.D. Phillips at the Plenary session of the Pontifical Academy of Science, which met at the Vatican during 25-29 November 2016. The material here is informed by work at the US National Institute of Standards and Technology (NIST) on the electrical power grid in the United States. We are grateful for input to this paper from our NIST colleagues, Allen Goldstein, Thomas Nelson and Gerard Stenbakken.

While the title of this paper is "Efficient use of electrical power", in keeping with the theme of the plenary session *Science and Sustainability*, in fact, the paper is about the "Smart Grid". The idea is that to meet the needs of a future in which electricity is generated by sources throughout both transmission and distribution grids and used in a sustainable manner, we will need a flexible and responsive replacement for the existing infrastructure – that is the Smart Grid [1, 2].

Today, electricity in the US is, for the most part, distributed by the "legacy" electric power grid, the system that was developed during the over 120 years that preceded the idea of a Smart Grid [3]. In the legacy grid, electricity is generated in big, static generating plants. Those plants produce alternating current, transform the voltage up to very high voltage to minimize energy losses over long distance transmission grids, and then, at the customer level, they transform it down in distribution grids to a voltage that depends on the customer: whether it is a big or a medium or residential size customer. A key feature of the legacy grid is that it provides a one-way process (which is something that Steve Chu emphasized in his talk, where he mentioned the legacy system): You make electricity in big static power plants and you deliver it to the customer.

The idea of the Smart Grid is to do lots of things that go beyond the static and one-way paradigm of the legacy grid. One feature is to have a much more diverse system where users may in fact be generating electricity by a variety of means. For example, residential users might be generating electricity from solar panels installed on their home. Bigger installations, like factories and apartment buildings and offices, might be generating electricity for use locally, for example in microgrids as Steve Chu mentioned, and also sending it back into the larger grid. Microgrids, which are self-sustaining and can operate for limited periods when the larger grid suffers a power outage, may become more prevalent as renewable resources such as solar, wind, and battery storage for electrical energy get increasingly higher penetration into electrical distribution systems [4].

In order to achieve the desired benefits of a variety of sources of generated electricity, one needs to have energy storage. As we have heard, batteries are getting better all the time, so we hope that batteries will be an increasingly important and efficient part of the energy storage landscape. We heard from Steve Chu about pumping water into elevated tanks as an energy storage strategy, and find this appealing. During our youth, many farms in the United States had windmills, which looked just like the picture that Steve showed, pumping water to store energy. It was a good idea then, and it is satisfying to know that it remains a good idea today. Of course, we have heard that there are lots of other ways to store energy. For example, batteries are an essential part of plug-in and hybrid electric vehicles that may play a role in energy storage in the grid of the future [2]. One can also use electricity to make fuels for later consumption. While the details of energy storage are important, these are not the focus of this presentation.

An important feature of the Smart Grid is that it will be more of a web than a radial arrangement. The legacy grid is mainly radial, with centralized generation, radial distribution, and a relatively static structure. A good feature of such a system is that one can predict its behavior. By contrast, in the future we will be better able to control and adapt to changing electric system behavior by using smart grid systems. We hope to have a high penetration of renewable sources, and a lot of those renewable sources are going to be variable. For example, when the wind blows, you generate electrical power, and when it doesn't, you don't. When the sun shines, you generate electrical power and when it doesn't, you don't. We also expect a high penetration of variable loads, for example electric vehicles. If everyone has an electric vehicle and they all come home at 5:30 and plug them in, that will produce a big jump in the demand for electricity that is different from what we experience today [3]. This dynamic nature of generation and demand is going to make things a lot more complicated.

The difficulties with that kind of a system are akin to the difficulty of predicting the way in which some sort of a neural network might work, a complex problem that presents significant challenges. As one illustration of the kind of challenge that might become more prevalent in the future, consider an incident from a few years ago when a power plant in Florida went off line. In a matter of seconds, the disturbance from that incident spread throughout the entire eastern part of the United Sates [5]. The grid needs to be able to respond to incidents like this within seconds and incidents like this are likely to happen more and more frequently as we transition to a less static electrical grid structure.

An important contributor to the dynamic nature of the grid is weather. We have been seeing a near-linear increase in the kind of weather-related events that cause power outages, and this has resulted in significant costs, measured in billions of US dollars per year. An important connection to sustainability is that a lot of people believe that this increase in weather-related events is due to climate change and that it is going to get worse if we as a world community don't transition to a more sustainable energy economy. Furthermore, weather-related events become more and more of an issue the more complex the grid becomes, and the grid must become more complex in order, at least in part, to handle all of the renewable resources.

To build a Smart Grid that can respond to an increasingly dynamic environment, whether the dynamics come from variable generation, variable demand, weather events, or whatever, we need real-time information about what is happening. This is where NIST, as a metrology laboratory, comes in: reliable and useful information derived from accurate measurement.

Among the things we need to know about the grid are the amplitude and phase of the electric current and voltage at a lot of different places. Furthermore, we need to know these parameters in real time. Here, the capabilities of a National Metrology Institute like NIST are crucial. At NIST we know how to measure electrical parameters, and we know how to time-stamp them so that everybody who receives this information is able to know exactly what's happening simultaneously over the entire grid. This is, of course, not the only information that is needed, but having this information is one of the requirements to do what we want to do with a Smart Grid.

As an example of how a metrology laboratory can improve the capabilities needed to operate a Smart Grid, consider the case of a certain model of a Phasor Measurement Unit (PMU) [6]. These units measure, among other things, the current, voltage, frequency, and rate of change of frequency at locations throughout the grid, reporting those parameters and the time of the measurement. These data can be used by the Energy Management Systems that determine electric power system states and power flows, and control the grid. NIST measurements showed that some of the measured parameters varied from the true values by nearly 15%, exceeding by far the specified limits for PMUs [7]. Identifying these difficulties allowed the manufacturer to make modifications that brought the typical accuracy errors of the PMUs to better than the required 1%. Getting this kind of high quality data is one of the essential requirements for the operation of a Smart Grid.

As mentioned earlier, a feature of a more sustainable future is that there are going to be microgrids: local communities will have their own grids; they will produce electricity; they will use it internally; they will sell it back to the larger grid. This will create both opportunities and challenges. Renewable sources, sustainable but variable-demand end-use, microgrids, and other features beneficial to a sustainable future will be easier to integrate into to our general electrical power system, if we have the kind of intelligence in our Smart Grid that is both measurement and response. I've only spoken about measurement in detail, but obviously response is equally important. As Steve Chu indicated, we need things like machine learning to figure out how to respond to the kinds of changes that a future Smart Grid is going to experience.

We end with this thought: that the instrumentation for the Smart Grid, and the reliable measurements from that instrumentation, areas in which metrology laboratories like NIST excel, are among many technological developments that we need for a sustainable energy economy.

References

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[4] How Microgrids Work, US Department of Energy, (2014)

[5] Florida Blackout 2008, frequency disturbance propagation in Eastern Interconnection of the US Power Grid as observed using FNET. See video at https://www.youtube.com/watch?v=H7y-oJYpDkM. For further information on FNET see website: http://fnetpublic.utk.edu/

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