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## Kirchhoff's Laws Cannot Be Repealed, Legislated or Ignored

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The events in California that led to what is now referred to as the “meltdown” have surfaced several new problems for the electric-power industry. The case study that will eventually describe what happened is named the “Perfect Storm,” a title meant to reflect the fact that everything went wrong and at the same time. Most agree that the bulk of the problems were the result of serious flaws in market design, generator capacity shortages, high prices for natural gas, a tightening of environmental controls and what can only be referred to as political tampering. There was an almost-blind faith that economic benefits would be produced if an open market of any type were created. However, the design of such markets has proven difficult for the electricity business and California was the wake up call. One reason among many: engineering characteristics of the transmission and distribution (T&D) system must be accounted for in market design. Who has the knowledge and expertise to accomplish this? Certainly not the economists alone and certainly not the engineers alone; working together, they have a chance.

Let's face it, the current T&D system was designed by engineers to support marginal-cost operation of generators in a world of reasonably predictable inelastic load demand. Most agree that for electricity markets to work, load demand cannot remain completely elastic. In addition, we can say that electricity is a unique good. It cannot be stored without a substantial infrastructure, such as pumped storage facilities, and thus most of it is produced and delivered instantaneously through extensive networks of power transmission lines collectively known as “the grid.” It is fair to say that all power outlets in the country are electrically connected by means of this grid. Yet, we do not know how to design T&D systems to accommodate markets that may exhibit volatility from time-to-time and that may deviate substantially from traditional operation. A principle reason is that Kirchhoff's laws, which are laws of nature, must be integrated with man-made economic doctrine.

### **Kirchhoff's Laws**

Kirchhoff's laws apply to every interconnected electrical network, whether it is inside a radio, a cell phone or a power grid. Kirchhoff's law for currents in these networks simply says that if all the currents flowing into any node in the network are summed, their sum must be zero. There is a similar law for voltages and both must be obeyed. If we think of a node as an intersection in a highway network, there are several choices about the direction we could go next: right, left or straight-ahead. We could think of Kirchhoff's current law as a traffic cop directing cars at the intersection, not on the basis of where the drivers want to go, but rather, on the basis of making sure the flow on each connecting road is balanced in some sense. That is, the “mother-in-law” principle — a principle in the airline industry that says if your mother-in-law is inserted into a point in the system, you have every right to expect her to come out at another pre-specified point — doesn't hold for electric grids like it does for airlines. Electrons produced by generators cannot buy a ticket to a destination of their choice.

Voltages in an electrical power grid are tightly controlled, therefore, we can think of power as analogous to current. So requiring power to flow from point A to point B in an electrical grid means

you must have the ability to control the direction of the flow at every node in the system.

### Effect on Open Markets

While many industries such as air-travel, gas, truck and rail have undergone radical transformations to ensure that an open market structure exists, none have had to contend with physical laws that are akin to Kirchhoff's Laws for an ac network. The flows produced by these laws can produce unexpected and/or unintended market responses. Without the flow control devices that exist in all of the other deregulated industries, electricity will be a difficult commodity to govern with simple markets. And so far, flow control devices are prohibitively expensive and difficult to engineer. So, for the foreseeable future, we are stuck with Kirchhoff as the traffic cop.

Kirchhoff's laws govern electric flow from a macroscopic perspective. Voltages, phase angles, and active and reactive injections must always obey Kirchhoff's laws. Constraints are imposed by Kirchhoff's laws and other operational factors such as voltage limits, line thermal transfer limits, generator capacities and other limits that have their origin in grid security considerations. Electric power markets are not the only markets that exhibit constraints in the minimum-cost scheduling problem. Gas delivery over pipelines is subject to pipeline congestion; airline traffic is subject to the capacity of hubs. The economic theory that provides the basis for the efficient operation of these markets can accommodate linear constraints easily. However, the physical constraints imposed by the grid are in general much harder to model than the (usually) linear constraints found in the markets for other goods. For one thing, many *state variables* in addition to generation quantities must be considered in the optimization problem. Voltages, phase angles, phase shifter and transformer tap settings, and switched capacitor banks all enter the problem in one way or another. In addition, the constraints imposed by Kirchhoff's laws are highly nonlinear. Finally, many other engineering constraints, such as thermal transfer limits, are also complex nonlinear functions of the state variables. In the course of researching other aspects of deregulation in the electric power industry, my colleague Carlos E. Murillo-Sanchez and I have surfaced many examples that are in contrast to the more predictable congestion issues in the markets for other goods.

Therefore, the network and all of its complexities must be considered from the initial market design — not as an afterthought. Otherwise, the physical operation of the grid can deviate from an idealized market exchange. There's no getting around Kirchhoff's laws.

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Note: For detailed analysis, see IEEE Paper #0-7803-6674-3/00.

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