Electricity Advisory Committee

TO: **Honorable Patricia Hoffman, Assistant Secretary for Electricity Delivery and Energy Reliability, U.S. Department of Energy**

FROM: **Electricity Advisory Committee (EAC)**
Susan Tierney, Chair

DATE: **September 29, 2016**

RE: **The Value of a VAr – Perspectives on Electric Grid Voltage Support**

Concept and Goals of This Document

The core purpose of this white paper is to delineate between two crucial forms of power supplied by and to the nation's electric grid(s). The need for the first—the "real" power that comprises the ability to light the nation; run motors and other devices that drive economic growth; and deliver water, gas, oil, and other necessities of modern life—is almost universally understood. The existence of, much less the need for, the second form ("imaginary" power) is less well understood by the general public. Still, within the electric grid's community of major stakeholders, the need for "imaginary," or what is more commonly called "reactive" power (or volt-ampere reactive, VAr) to supply voltage support to the grid is well recognized.[1] This paper delineates further the differences between the concepts of steady-state and dynamic voltage support.

This paper attempts more ambitiously to bridge gaps between important perspectives on voltage support—which are sometimes very different and determined by whether an individual or group has a background in power system planning, advocating for environmental improvement, setting policy, regulation on behalf of constituent/consumers, or in a myriad of other important roles. The paper also attempts to provide well-delineated information to draw

[1] Real power involves voltage and current waveforms that are "in phase," meaning that the peaks of the respective waveforms coincide in time, such that it performs maximum work. (The governing equation: power = voltage **x** current **x** the cosine of the angle between them yields maximum power in this case, since the cosine = 1, when the two are in phase.) Imaginary power—or reactive power—its interchangeable, and better used term, unless discussion is confined to only electrical engineers, is unable to perform any work. (The voltage and current are 90 degrees out of phase for reactive power, so the cosine term in the equation = zero.) However, reactive power performs the useful role of supporting relatively local grid voltage, so that the grid does not experience voltage collapse as real power moves across it from remote sources to locations where work is needed. Real power is measured in watts, kilowatts, or megawatts. Reactive power is measured in VArs (volt-amperes reactive), kiloVArs, or megaVArs. A more complete mathematical explanation of electric power and its real and reactive components with illustrations can be found in Appendix A.

all stakeholders into a more informed discussion through a common vocabulary and understanding of the complexities of grid voltage support.

The links are necessary to leverage the strengths of various perspectives to provide the best set of consensus recommendations to the Department of Energy (DOE) regarding its further role and activities in research, development, demonstration, and education related to continued reliable grid voltage support.

Illustrations of the Gap That DOE's Electricity Advisory Committee Seeks to Close

An array of examples could be supplied to support the need for this paper—some well publicized, others less so. All too often in either case, their outcomes can be critical to future development of energy policy and/or continued reliable grid operation. Typically, these cases involve an argument regarding electric service needs and future arrangements to meet requirements. Alternatively, cases involve differing perspectives on why electric service failures *have occurred*. A fundamental misunderstanding of service needs is commonly found across these instances: much attention is given to the available supply of real power to an area, while the need for reactive power (and particularly dynamic reactive) is completely ignored.

Two examples are provided in an effort to illustrate that this misunderstanding can and does occur in quite unexpected places.

The first involved a very public exchange of opinions in April 2015 between a nationally respected newspaper's editorial board and a successful business, political, and environmental leader regarding a local disturbance to electric service in an important city in the United States. The newspaper argued that had a retired, local power plant still been available to supply power to the area affected by the disturbance, the service issue might have been avoided.[2] The business leader responded that the retirement would not have helped, and was a wise environmental decision. Two other letter writers weighed in before the press cycle passed.

The relevance of this example is that the event was initially described by the paper as a "dip in voltage that cascaded across the grid," and nowhere in the ensuing discussion was this disputed. Yet, all of the statements offered thereafter were either explicitly or implicitly (and incorrectly) framed in terms of whether adequate real power was available to prevent the event, rather than addressing the reactive power[3] whose role it is to support voltage.

The second example occurred not in the press, where wins are determined by the court of public opinion, but in an actual court of law.[4] An expert witness for the plaintiff testified that certain generating units could be retired immediately based on the surplus capacity of real power available from other sources. Absent in his testimony was any reference to the very necessary reactive power, also supplied by those units to the area, or to the considerable time necessary to construct local replacement sources for the reactive power in order to avoid area voltage collapse. While real power can be carried by transmission lines for long distances before it does work, reactive power has to be supplied more locally in order to provide voltage support.

[2] "Washington's 'Beyond Coal' Blackout," *Wall Street Journal*, editorial, April 13, 2015.

[3] Experts were immediately analyzing the event and revealed their findings months after the newspaper exchange in the report, "April 2015 Washington DC Area Low-Voltage Disturbance Event," published on September 16, 2015, by the North American Electric Reliability Corporation. Neither the problem nor its identified causes matched the earlier public exchange.

[4] In the District Court of the United States for the Western District of North Carolina Ashville Division, Civil No. 1:06CV20, State of North Carolina, ex rel. Roy Cooper, Attorney General, Plaintiff, Vs. Tennessee Valley Authority, Defendant.

The first case brings to mind the increasing number of predictably counterproductive debates that occur particularly in the media today. Participants argue from deeply held and profoundly contrary initial positions. Ironically, common ground, even “win-win” compromise, is usually available, but only if the principals involved are committed to the hard work of *good faith* debate. This requires that they must possess a mutual desire to embrace deeper and more nuanced understandings of the particular issue at hand if these become known during their debate. As long as the parties argue past each other while clinging to incomplete and sometimes fallacious “understandings,” little of value can result. The second illustrates the need to seek counsel from more than just one expert in order to close gaps in knowledge and understanding before making important decisions.

This work product is offered as a collaborative contribution toward productive, intelligently framed discussions on the “value of a VAr.”

Unconventional, if Not Unique, Organizational Basis of “The Value of a VAr” as a Technical Document

The organization of this paper intentionally mimics William Faulkner’s first major novel, *The Sound and the Fury*. *The Sound and the Fury* is an account of the Compsons, an aristocratic Southern family in decline in the early 1900s. Faulkner develops the novel in four parts. Each of the first three parts is written solely from the perspective of a different son in the family. The fourth is written in the omniscient third person, and pulls together threads from the first three.

Similarly, “Value of a VAr” is written from distinct grid perspectives that include the system/transmission planner, the environmental stakeholder, the policymaker, and the regulator. The final section of the paper then brings these viewpoints together.

Literary critics have acclaimed Faulkner’s genius for his telling the first part of *The Sound and the Fury* from the perspective of the 33-year-old, severely mentally challenged, youngest Compson son, Benjy—commonly, albeit insensitively, referred to at the time of its first publication as an “idiot.” Alternatively, some have noted that each of the Compson sons exhibited his own respective idiocy. In fact, some of the richest nuances of the narrative proceed from the impressions and memories of Benjy. His contribution is as important to the novel’s success as the section written from the omniscient third person that serves to tie the entire work together.

In like fashion, none of the various perspectives on grid voltage support is without great importance, and none is without some degree of idiocy—but all work toward an ultimate consensus regarding the value of a VAr. The varying perspectives should not be read with an expectation of point-counterpoint debate, or of competing viewpoints from which one will emerge the winner. Rather, each perspective contributes to a mosaic representation or a full montage of what must comprise voltage support for the future electric grid. While this paper will not accomplish that perfectly, it will *not* commit the idiocy of willfully neglecting any of the various perspectives, or worse, of marginalizing the valid contribution supplied by any. Each perspective is developed essentially independently to ensure that no nuance from any is lost.

What Is a VAr?

In alternating current devices, current is pulled from the grid for two purposes. The first is to provide energy to produce an effect (e.g., light, motion, or heat). Many devices however depend upon the creation of a magnetic field before the powered effect is produced. Examples of such devices are transformers, motors, and electromagnets.

In an alternating current device, the creation of this field, consuming current, is followed immediately by a reversal of current and collapse of the magnetic field. When the field collapses, all of the energy in the field is returned to the grid, creating a repeated storage-then-return-of-energy 60 times/second.

Since all of the energy is returned, the current provided to these devices is not associated with “real” power to produce an effect and the appearance of power being transferred was originally called “imaginary” power. Not being “real” power, the use of watts to describe it was incorrect and this current was accounted for in the power grid as a volt-ampere “reactive” or VAr, and is now referred to as reactive power. The following Figure provides additional clarification.

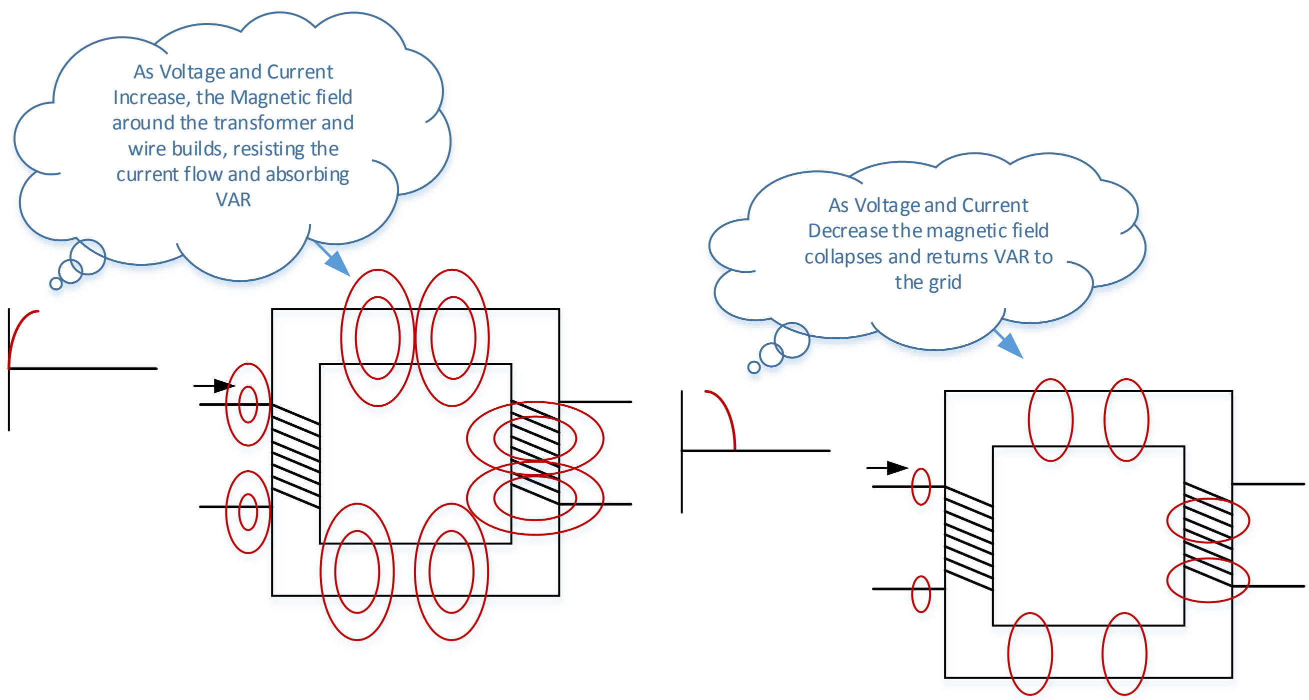

Figure 1. *Impact of Voltage and Current Increases and Decreases in the Context of VAR*

Role Envisioned for DOE

The ultimate role envisioned for DOE regarding VAr is for the agency to act as the catalyst to direct and harness advanced efforts by academia, national laboratories, research beds, and all segments of electric grid stakeholders to fully answer the extremely complex question, “What is the value of a VAr, and how and where to best provide it?”

This requires DOE to press far beyond the scope of this paper—which is limited to providing a common understanding that sufficient VArs must be available today to avoid grid collapse simply as a cost of service, and that consistent and full consideration of all available sources of those VArs (both steady state and dynamic) comprises only t minimum threshold of adequate transmission planning. Further, prudence demands that no new technology promising to supply VArs to the grid be deemed an available source of grid VArs until it has been fully vetted for reliable operation within the grid environment and for the specific need that is driving its application.

In contrast, DOE's role will involve developing and championing such a complex future understanding of VArs that markets or vertically integrated utilities can provide them to the grid not as a cost of service, but on the basis of their incremental value—a complex value dependent upon specific grid location or type of location, across various times and circumstances, and under a range of grid configurations. As described in later sections of this paper, there may be a number of ways that providers of this service can be compensated.

PART ONE – Transmission/System Planning Perspective

The Value of a VAr: Exploring the Evolving Role and Requirements for the Volt-Ampere Reactive to Support Grid Reliability

Introduction

The first electrical grids in the United States were small, typically consisting of a local source of generation (often hydro) and the wiring necessary to light a town on demand—and also supply any industrial motor load made possible by the grid's proximity. The generator supplied any voltage support required as well as the real power that made life suddenly so much easier for those with access to these initial grids.

As these isolated power grids expanded—sometimes to reach new, more distant concentrations of residential or industrial load and later, to intertie with other grids for efficiency and reliability improvements—voltage support was sometimes necessary close to load concentrations that were too distant for the generator(s) to meet the need. A synchronous condenser was often installed in this circumstance. A synchronous condenser is a motor that is designed in some ways similarly to a generator, so that it can raise or lower system voltage around it. However, since it lacks a prime mover to turn it (e.g., a waterwheel or coal-fueled, steam-driven turbine), it consumes electricity while regulating voltage rather than generating it. Capacitors, currently the most frequently used electrical device to provide system voltage support distant from generation, were at this early time quite unreliable, and were not available in sizes to supply significant voltage support.

Voltage support from generators and synchronous condensers flows instantaneously to the power system when needed—a result of the inertial properties of rotating machines, and the laws of physics that govern electricity—even before their exciters initiate further quick action for regulation. These immediate responses comprise dynamic voltage support. Capacitors, on the other hand, must be switched onto the power system to raise local voltage, and switched off the system to lower it. This action typically takes from thirty seconds to a minute because of intentional delay to ensure the operation is actually necessary. This delayed response is referred to as steady-state or static voltage support. Generators and synchronous condensers can supply both steady-state and dynamic support. By virtue of which devices were available, reliable, and suitably sized, however, all early voltage support could essentially flow dynamically if needed, at a time when mere steady-state voltage support would have sufficed. Voltage support was also for obvious reasons concentrated at the generation sites.

The early grid was rich in dynamic VArs to supply voltage support, but this dynamic support comprised a solution in search of a problem.

Since then, capacitors have dramatically improved in performance and cost. Capacitors long ago replaced synchronous condensers as the support device of choice because they had lower initial cost, lower maintenance cost (no rotating machine to service), much lower electrical losses—and upon reaching a certain stage of their development, higher reliability. As an example, in a typical grid modeling case for the Eastern Interconnection today, there are 75,884 net mega VAr (MVAr) available from generators, 40,566 MVAr from capacitors, and negligible MVAr from synchronous condensers (values are steady-state, and even then, a bit simplified). During most of the intervening years, the need for dynamic support was simply not a factor in any decision matrix. The need did not exist.

By 1987, however, threats of local and even wide-area voltage collapse were emerging that could be mitigated only by dynamic voltage support supplied within the threatened area—usually combined with other measures. Increased penetration of highly concentrated residential air conditioning load increased the probability that large pockets of its low-inertia induction motors for gas compressors would stall and cause cascading system collapses—under certain grid conditions—from a phenomenon that has now been named Fault-Induced Delayed Voltage Recovery (FIDVR). As new types of load are increasingly being tied to the grid in the 21st century, with characteristics that are not yet completely understood, even more dynamic VArs (or some other measure) may be needed to mitigate "unadvertised features" that surface at some point.

Idling or retirement of coal units or other conventional generation can significantly reduce the headroom margin of VArs in an area, or even result in an inadequate supply of VArs there, unless replacement sources are provided. This could exacerbate an existing threat or create a new one, so very detailed and complex dynamic system impact studies must be conducted to inform these situations before taking any such action. Sometimes replacement generation using a cleaner fuel is the solution—most often today with single cycle gas turbines (SCGT) or combined cycle units (CCGT), depending on required run cycles. Alternatively, generators can be converted to synchronous condensers, or new machines can be installed in situations where this is more economical than conversion. More recently developed power electronic sources of dynamic VArs might also be installed. These include the static VAr compensator (SVC), which very quickly switches fixed increments of voltage support onto and off of the system as needed, and the static synchronous compensator (STATCOM), which can essentially supply any value of support within its design range instantaneously. The STATCOM costs more than the SVC, so it is typically only used when a solution requires extreme speed and efficiency unavailable in an SVC.

Current circumstances present a challenge to system planners, particularly the much smaller cadre of transmission planners that specialize in stability studies. These specialists consider extremely short time intervals in great depth. Even studies of a very small grid area to determine if more dynamic voltage support is needed are usually quite complex. Resulting recommendations are difficult to explain to those not intimately familiar with power system behavior. Confident determination of how much dynamic support is needed is not trivial. Successfully obtaining in-house and/or external approvals to fund it can be even more difficult.

DOE could assist the situation in several ways, including:

- Conduct R&D to codify, standardize, further enhance, and educate the industry to stability study best practices
- Encourage educational measures (to include acceptance and distribution of this Electricity Advisory Committee white paper) that capture and leverage a variety of sometimes competing, but equally valid, perspectives on grid voltage support—with emphasis on establishing a methodology to reach consensus on how much dynamic versus steady-state support the grid requires in a given area, and perhaps (joint or sole) delivery of industry workshops to address reactive issues and to promote a common understanding based on the best aspects of all perspectives.
- Explore continued educational measures (DOE has jointly conducted several of these) that specifically emphasize a range of dynamic modeling issues including, the FIDVR phenomenon and its causes, modeling, signature grid vulnerabilities, relationship to protection and control philosophies employed, and potential mitigation.

- Support R&D conducted by national laboratories and other strong theoretical academics (guided by a wide variety of grid stakeholders as well as electric grid planning and operating experts) to develop a common language, understanding, and a broadly supported metric to communicate the value of a VAr at any point on the grid for a reasonable variety of circumstances, which can drive incremental grid investment decisions for dynamic VArs.

Moving Beyond a "Beer Mug" Understanding of Reactive Power

The most widely shared illustration of reactive power contrasted with real power—the foamy head and cool, refreshing liquid present in a beer mug—has been quite effective for its intended purpose since at least the 1970s (see Figure 2a and 2b). However, this has always been a limited application, used to explain the need for power factor penalties[5] for industrial, commercial, and aggregated residential loads that could not maintain a power factor typically between 95 percent "lagging"[6] and unity (i.e., no reactive, all real power). Those penalties were established to be steep enough that they incentivized customers to pay for power factor correction (consisting of capacitors in parallel with offending loads) because their installation was considerably cheaper than paying the penalties over time.

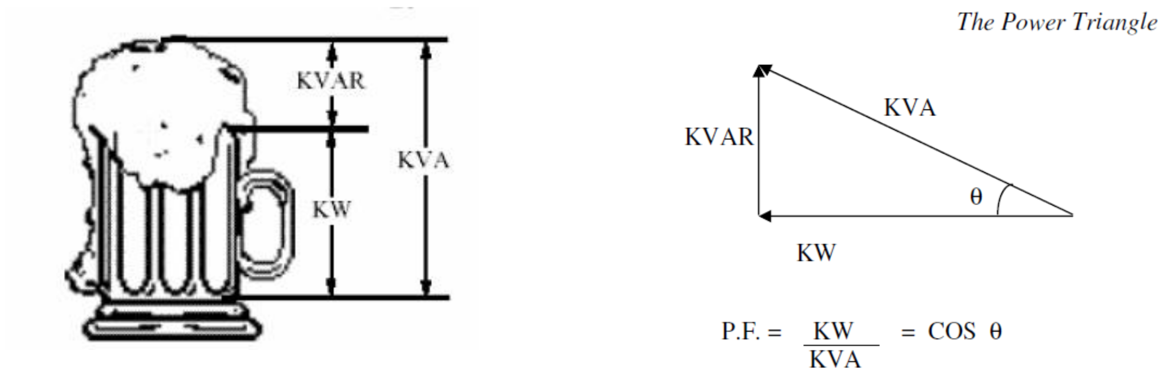

***Figure 2a and 2b**. Model of the beer analogy and the power triangle. Adapted from "Power Factor – The Basics," by PowerStudies, Inc.*

The explanation associated with the beer mug analogy was that in alternating current power systems (as in the human body!), the liquid beer actually performed the intended work desired. However, the generator had to supply, and the transmission and distribution lines had to carry, the greater apparent power required (the KVA of Figure 2b) because the load's additional foamy head provided no benefit to the customer. The reactive foam could be reduced to a value that incurred no billing penalty by adding a properly sized, local capacitor bank in parallel with the load—also referred to as connected in "shunt" with the load, or called simply, a "shunt capacitor." This would reduce the load's reactive power requirement from the grid (not—it must be noted—because the characteristic need of this load for reactive power had been eliminated, but only because the

[5] Power factor (P.F.) refers to the mathematical cosine of the angle between real power (kilowatt, kW) and apparent power (kilovolt-Ampere, KVA) as illustrated in Figure 1b above. The cosine of a 0 degree angle is the numeral 1. The cosine of a 90-degree angle is the numeral 0. Utilities assigned billing penalties to large customers whose power factors were inefficiently low.

[6] At the time, essentially all grid loads such as incandescent lighting and motors were "lagging," or inductive, which just means that the current through them peaked after of the voltage across them peaked when viewing these waveforms on electrical measuring devices such as oscilloscopes. Had they been purely resistive, the P.F. would have been unity (1), and there would have been no reactive component to the load.

capacitor would now meet this need locally and relieve the grid of this obligation). With the multiplying effect from local correction of the grid's many reactive loads, capital investment and other associated societal costs could be avoided for additional generation and/or line capacity. The savings could be passed through to the rate base. Further, the penalty ensured that if the load did not correct its power factor, those additional costs of service would appropriately fall to the owner rather than be socialized. Billing penalty pressure increased in scope and magnitude as the larger benefits of conservation were widely accepted throughout the 1970s.

The beer mug remains an excellent illustration within the limited billing application. However, today's grid stakeholders need to understand the mug within a larger context of grid reactive power.

There are two fundamentally different categories of grid elements that require reactive power. The first, as just discussed, is that of loads connected to the electric grid—whether large concentrated industrial loads, or much smaller residential and commercial loads that can be effectively aggregated to supply their reactive needs with a common capacitor installed at an upstream substation. The second consists of elements that actually comprise the electric grid, such as transformers and transmission lines.

For example, each generator's step-up transformer (GSU) is a large consumer of reactive power, requiring MVArs sometimes in excess of 20 percent of the megawatts flowing through it. A GSU accepts power from its generator at a voltage typically around 25 kV, and will inject that power onto the grid at a much higher voltage—up to a maximum of 765 kV in the United States. The low-side voltage is limited by practical considerations related to providing internal generator insulation. The high-side voltage enables lower transmission losses for long distance power flow. As the voltage is increased by transformer action, the current correspondingly lowers, and the largest component of power transmission loss is proportional to the square of the current. Since the GSU is at the generation site, it makes sense for its reactive requirement to be supplied by its generator.

Additionally, transmission lines themselves sometimes consume reactive power. A transmission line acts as a capacitive element and generates reactive power, below what is called the surge impedance loading (SIL). However, above the SIL value, the line acts inductively and consumes reactive power. Areas within the larger power grid can significantly compromise reliability if, for instance, unexpectedly high loop flows occur and lines suddenly switch from VAr producers to heavy VAr consumers. Historically, conventional generation has been dispersed such that it was usually the most effective and economical means of supplying not only real power for loads, and reactive power for GSUs, but also reactive power to mitigate transmission impacts.

Exceptions have occurred when unusual changes in grid loop flows have suddenly pushed lines above their SIL and "flipped" them from reactive power producers to heavy consumers without benefit of prior study within utility/industry planning processes. Typically, these exceptions have been mitigated for the future by installing economical steady-state VAr solutions, such as an appropriate number of large, switched capacitor banks dispersed at various substation buses throughout an area.

Despite the exceptions, the general rule will most likely continue to be true for areas in which retired generation (usually conventional) is replaced at or near its same site. However, opportunity exists whenever local replacement is unnecessary for any reason, such as economically driven load reduction or increased energy efficiency/demand reduction (EEDR), to explore what optimal grid placement of alternative reactive sources might look like in the absence of these stalwarts. (The exercise of this opportunity must be conducted with great care lest grid reliability be unwittingly compromised in the process, as will be illustrated in detail later in the paper.)

Compensation for reactive consumption by each step-down transformer might come in whole or in part from nearby grid generation, from an extra-high voltage system (765, 500, or 345 kV) loaded below SIL, or by placement of local capacitor banks primarily for end-use load correction.

So, while the mug analogy is still very useful in convincing customers to reduce their foam by installing economical, local correction—the grid will always require its own measure of reactive power. It simply cannot move real power significant distances without reactive power to prevent voltage collapse. A typical transmission planning rule of thumb is that 1 MVAr is required on the grid for each 3 MW moving across it. The siting of that MVAr is not a trivial process.

Emergence of the Fault-Induced Delayed Voltage Recovery (FIDVR) Issue Requires Dynamic Voltage Support for Mitigation

On August 22, 1987, the first documented case of what was later to be termed an FIDVR event occurred, resulting in the loss of 1265 MW of load from Memphis, Tennessee, that extended northeast to the area surrounding Jackson, Tennessee.[7] The phenomenon has repeated elsewhere many times since, with strong documentation. FIDVR events are addressed in a North American Electric Reliability Corporation (NERC) technical reference paper on the topic,[8] which also provides the first industry-approved definition of FIDVR. Both of these references include more technical detail than presented in this paper.

FIDVR results from high concentrations of induction motor load within an area of the grid, usually of low-inertia, residential air-conditioning motors that under certain conditions (e.g., high local grid loading, high percentage of the load comprising air-conditioning, often accompanied by reduced availability of dynamic VArs to support the local grid) can initiate voltage collapse for faults that under "normal" circumstances would clear quickly.

The reason for this is that low-inertia loads such as residential air conditioners can easily stall for voltage reductions of short duration and begin to operate in the "locked-rotor" mode. In this condition, the compressor motors consume four to five times their normal operating reactive. The increased reactive load can cause the voltage to stay depressed after the initial fault has been isolated from the grid, and the air-conditioning load will eventually trip, not by under-voltage protection (because residential units are not equipped with this), but by compressor thermal protection as their compressor motors overheat to the point where they must be protected against permanent damage. Less sensitive induction motor loads such as water system booster pumps can exacerbate the event as the local grid voltage depression extends.

If enough essentially simultaneous load shed occurs as loads protect themselves against the impact of reduced service voltage, the grid can transition quickly from an under-voltage situation that threatens loads to an over-voltage situation that threatens the grid as well. The grid is designed to meet Institute of Electrical & Electronic Engineers' (IEEE) standards that recognize the importance of insulating it both effectively and economically. Extra-high-voltage (EHV) grid elements (345, 500, and 765 kV) are designed to withstand voltages up to 5 percent above their rating. Lower voltages than this typically require that elements withstand a 10 percent

[7] G. C. Bullock, "Cascading Voltage Collapse in West Tennessee, August 2, 1987, Georgia Tech Relay Conference, Atlanta, GA May 1990.

[8] "A Technical Reference Paper: Fault-Induced Delayed Voltage Recovery," Published jointly by NERC's Transmission Issues Subcommittee and System Protection & Controls Task Force, March & June, 2009.

overvoltage. FIDVR events with loss of load can drive grid voltages beyond these design requirements and potentially cause damage to grid elements such as circuit breakers, transformers, and line (or "bus") insulators. Even without permanent damage, an FIDVR event can entail an unacceptable sequence of voltage swings as loads automatically remove and restore themselves from and to the grid.

To date, there is no single, silver bullet solution to FIDVR. Air conditioners have been studied, both to determine whether more recent higher efficiency units were problematic relative to older, less efficient units, and to determine specific models' stall parameters with an eye toward solving FIDVR by the addition of under-voltage protection to residential air conditioners. It has been shown that increasing penetration of air conditioning rather than the advent of higher efficiency units is driving increases in FIDVR events. The residential unit level under-voltage protection could serve well as a component within an effective FIDVR solution strategy, but would not constitute a stand-alone solution. Adding VArs to the area to provide additional voltage support can work, but these must be dynamic VArs in order to mitigate FIDVR, which does not offer the luxury of a grace period within which steady-state VArs can be switched in-service. Further, even the dynamic VArs must be already available to the grid when FIDVR threatens in order to mitigate it. Generators, synchronous condensers, SVCs, and even Flexible Alternating Current Transmission System (FACTS) devices such as STATCOMS must be online prior to the threat in order to provide immediate effective voltage support.[9] [10]

Effective mitigation to prevent or limit FIDVR events or other cascades might include a combination of the following depending on local circumstances:

- Increase of dynamic VArs available to the local grid,
- Quicker clearing of faults (sometimes by means of the next bullet),
- More effective provision and coordination of transmission and/or distribution protective devices,
- Addition of air conditioning under-voltage protection at the unit level,
- Limiting impacted load, and
- Promoting energy savings to limit demand (especially air conditioning).

Southern Company provided a solution portfolio in response to an Atlanta Metro event in 1999 that is still impressive today. As noted in the NERC technical reference paper,[11] the comprehensive solution included:

- Installation of a 260 MVAR SVC,
- Relocation of key generating units from higher to lower voltage interconnections—effectively moving dynamic sources closer to loads,

[9] A 2007 FIDVR event in the Memphis area was contained to a loss of 600 MW. One difference in the two Memphis events was that one more local generating unit was online to supply dynamic VArs during the second event than in the 1987 event. Another was that NERC had by then put in place the Relay Loadability Standard, PRC-023-3. Compliance with this standard prevented relays from "seeing" excessive load current as fault current and tripping in cascading fashion as area lines carried increasing load currents as a result of lines that had tripped for the event.

[10] It should be noted (in the interest of completeness) that even if a capacitor bank could be switched quickly enough to mitigate FIDVR, the FACTS devices would still be more effective in doing so. The capacitor loses effectiveness proportional to the square of the voltage drop on the grid—FACTS devices retain effectiveness better, only degrading proportionally to the actual voltage drop. The rotating machine is the most reliable device, with greatest retained effectiveness.

[11] "A Technical Reference Paper: Fault-Induced Delayed Voltage Recovery," published jointly by NERC's Transmission Issues Subcommittee and System Protection & Controls Task Force, March & June, 2009.

- Conversion of a 500-kV transmission line to 230-kV operation—with the increased line impedance reducing the amount of load subjected to low voltage for FIDVR resulting from faults at critical locations,
- Planned new generation in North Georgia,
- A three-pronged strategy planned to mitigate multiple contingency events, which included faster breaker failure clearing at key stations, breaker replacements, and an
- Under-voltage load shed (UVLS) scheme.

Longstanding Dynamic Modeling Deficiencies and Improvements

The 1982 Memphis event was difficult to model, because:

- This event could not be duplicated using fault/load flow studies with conventional load models.
- Transient studies using lumped induction motor models as a portion of the load worked better but fell short of duplicating observed system voltage response.
- No real guidelines had been established to determine the nature of area summer transmission loads for large-scale voltage perturbations.
- Without an accurate study model, validation of mitigation efforts depended heavily on subjective reasoning. [12]

After the explanation of that event was published, but without improvement in dynamic models and study techniques for many years, it could only be determined whether a specific grid change was in the "direction of goodness" or "detrimental to FIDVR defense." Studies attempted to bound FIDVR issues while keeping mitigation measures as economical as practicable.

It was not until around 2003 that significant progress began to be realized in dynamic modeling. The much-improved models available today enable aggregation of air conditioning loads, but still do not support statements of absolute certainty that a particular mitigation plan has eliminated the possibility of FIDVR in an area. Dynamic models have improved significantly, but load research to guide their applications is still generally lacking. FIDVR study accuracy increases as the percentage of induction motor load versus resistive load is known for key grid busses, but this data is often missing and must then be estimated without benefit of research. Many utilities disbanded their load research departments years ago and have not yet recognized a need to reestablish them.

Further in 2016 and beyond, the vaguely defined characteristics of many new loads tying to the grid introduce so many unknowns into the planning process that research on their impacts under a full range of circumstances may be more urgent than increased refinement of the dynamic models or research on location of loads with known characteristics. Appendix B offers compelling insight into the contemporary system/transmission planning world.

[12] G. C. Bullock, "Cascading Voltage Collapse in West Tennessee, August 2, 1987, Georgia Tech Relay Conference, Atlanta, GA, May 1990.

The "Do-No-Harm" Approach in the Face of Uncertainty

Retirement of conventional resources on short notice, coupled with the level of modeling uncertainty that remains, can make a do-no-harm approach attractive when studying dynamic system impacts and determining grid upgrades for continued reliability. This is particularly true when vulnerability to collapse is already known to exist. If the steady-state and dynamic reactive power lost from the retirement is reliably replaced locally and in kind so that the do-no-harm principle is met for the retirement, then any additional collapse mitigation desired might come from exercising other available options, with particular emphasis on modification of protection and control schemes (to, for example, shorten the clearing time of a fault to a duration that does not threaten collapse).

Regardless of the philosophy used to mitigate FIDVR or other collapse mechanisms, it is vital that any and all elements included in mitigation plans be fully vetted to perform reliably the functions assigned to them.

Mistakes of Overconfidence That Must Be Avoided

The first high-power STATCOM[13] in the United States was commissioned in 1995, as an R&D pilot to test its use for several purposes including utilizing its supply of dynamic reactive power to prevent large area voltage collapse as winter loads increased with time. This STATCOM illustrates well the need for full vetting as mentioned above.

A fatal flaw occurred in its design, which was most likely the result of too much focus on the high-tech aspects of the device to the detriment of adequate communication with the designers responsible for the low-tech station service supply to its cooling pumps and control logic. Later STATCOM installations essentially repeated the same design deficiency for some years before widespread communication of its discovery first occurred. Further investigation found that the more mature and relatively cheaper SVC technology that preceded the STATCOMs bore the same Achilles heel when applied for the purpose of preventing voltage collapse if they were water-cooled rather than air-cooled. Figure 3 depicts this STATCOM configuration simplified for understanding of its station service power supply.

[13] Narain G. Hingorani and Laszlo Gyugyi, "Understanding FACTS, Concepts and Technology of Flexible AC Transmission Systems," Wiley-IEEE Press, 1999.

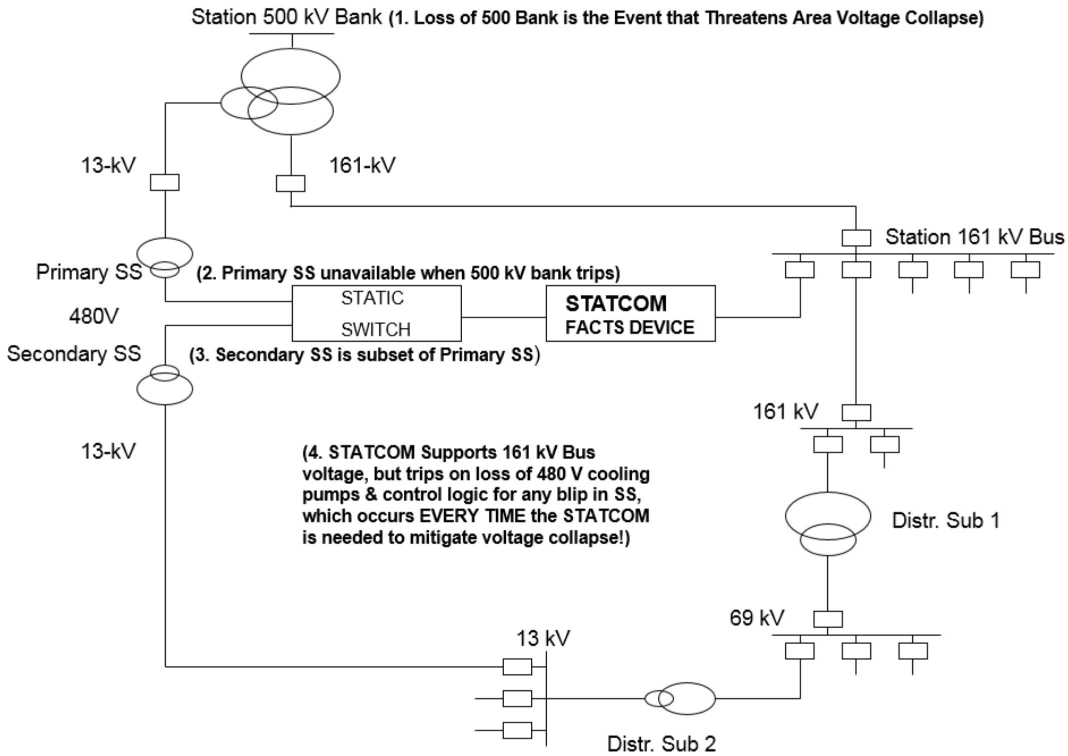

***Figure 3**: STATCOM Serial #1 Station Service – Still a common Achilles heel?*

It should be noted that reliability for any device applied to mitigate voltage collapse must be viewed differently than for other devices. Reliability must be defined and measured only with reference to the very narrow windows when voltage collapse in its vicinity is actually threatened, since that is the circumstance that justifies its installation versus the more economical capacitor banks that would have been sufficient for everything outside of these windows. Operation outside of these windows is irrelevant to the dynamic role to which it was assigned and expected to perform. However, when dynamic reactive generators such as this are installed, system operators typically use them to control steady-state grid voltage as well. Therefore, their reliability should be separately defined and tracked for their dynamic and steady-state roles. Ongoing discussion of this continues around IEEE Standard 859.[14]

Grid stakeholder communication and understanding of the configuration depicted in Figure 3—and of the need to diligently unearth other, similar issues that might prevent low-voltage ride-through of reactive generators—is still a work in progress, even within the utility planning community. It is reasonable to shine a light brightly on these issues as the application of reactive generators increases to support the grid's changing resource mix.

The problem with the initial wave of STATCOMs was that the designers of their station service supplies were not aware that they were vital to local grid reliability so designers applied standard station service templates. Typically, these provided for two sources of station service to the STATCOM cooling pump motors, and the second source was a subset of the first rather than being independent sources.

[14] IEEE 859-1987, IEEE Standard Terms for Reporting and Analyzing Outage Occurrences and Outage States of Electrical Transmission Facilities, is currently under review by committee led by Dr. Chris J. Dent.

Figure 2 illustrates a typical arrangement at the same time that it accurately depicts the particular details of the first grid STATCOM. The vulnerability to voltage collapse occurred under certain grid conditions for the loss of the local 500 kV transformer. Since the primary station service was derived from the 13 kV tertiary winding of the same transformer, the loss of primary station service to the cooling pumps occurred coincident with the threat of voltage collapse—by design. The secondary station service was supplied from the distribution grid—fed by the same 161 kV bus that the STATCOM was installed to support. Fast as it was, the STATCOM was obviously ill-equipped to save itself in this bootstrap arrangement. It was destined to trip on loss of voltage to its coolant pumps anytime that voltage collapse threatened. For the duration of the STATCOM's life, circumstances never aligned to threaten the voltage collapse for which its mitigation was being tested. Reliability was measured in standard terms of device availability to provide steady-state voltage support to the grid, and by this measure the STATCOM experienced periods of acceptable reliability punctuated by long durations offline to effect repairs or modifications due to its cutting edge technology. It was a significant time after its commissioning before utility maintenance personnel got familiar enough with the high-tech aspects of the valve hall, magnetics, control system details, and cooling system to take a step back and point out the Achilles heel of the device. The further question surfaced of whether the earlier generation of SVCs required similar cooling and whether other utilities had applied these devices with the same Achilles heel. This proved to be the case except in smaller, air-cooled devices (typically D-VArs.)

A general false confidence in these devices had grown over time because the lack of voltage collapse events was attributed to their application rather than to the fact that the grid circumstances that initiate collapse do not often occur—but when a collapse does occur, the societal impacts are large. The high-impact, low-frequency (HILF) nature of these events requires that solutions be challenged in part and in whole to ensure that they are adequate to their task.

Anecdotal evidence suggests that at least one utility had similar experience many years before when first applying synchronous condensers to the grid. Standard voltage protection was put in place to prevent their damage just as any large motor would be protected. It was only after the third low voltage incident—the synchronous condensers tripping each time, instead of supplying voltage support to the grid—that someone realized that they did not need voltage protection; they *were* the voltage protection!

Emphasize Reactive Margin for Resource Retirement…or Focus on Load as the Greater Future Threat?

Another instance of false confidence can originate from the mistaken use of tools intended only for steady-state resource operation, such as the manufacturer supplied Generator D-curve,[15] outside their intended scope, in the dynamic universe instead. This tends to occur anywhere that concentrated machine and stability expertise is not readily available, which could conceivably be interpreted to mean that this mistake might happen often—almost anywhere, almost anytime. Machine experts are few today.

A generator's mitigation of FIDVR or protection against most other voltage collapse phenomena is determined by the specific instantaneous response characteristic of the machine and its excitation system. Very short-term VAr injection for dynamic voltage support will usually be much greater than the steady-state VAr support that

[15] The D-curve, or what has also been called the "bull-nose" curve, details a generator's ability to supply or absorb reactive power at any real power production level within its range—useful in determining its steady-state reactive limit based on its thermal characteristics. It is not an appropriate tool for determining the dynamic reactive limit.

the generator can supply indefinitely. Its D-curve reflects its capability to supply the latter, long-term support without exceeding its thermal or other design bases.

A simple metric would be useful to convey the grid's relative abundance of, or lack of, adequate reactive power in an area. It would need to appropriately express statuses of both steady-state and dynamic reactive power available. Large changes or trends in the metric's value might be expected to result from such strategic decisions as conventional resource retirements and the grid upgrades offsetting them, or increased penetration of renewables. Development of this metric would require the attention of leading machine experts and planners, as well strong leadership from the most promising theoretical academics and research minds. To an unknown degree, the collaborative completion and adoption of the metric could offset for grid stakeholders the disadvantage presented them by the small number of machine experts available, and the difficulty of maintaining that function in-house, by giving them a chance to work together and build relationships.

However, as earlier stated, some eminent machine experts now assert that the most vital focus going forward involves understanding characteristics of new loads rather than generation. Replacement of incandescent lighting, for example, with compact fluorescent, liquid crystal display, or other technologies will provide a huge reduction of needed real power on the grid—at the cost of enduring a much less favorable power factor from the overall load. The impacts beg study.

These experts assert that while in the past the dynamic characteristics of the grid were defined by large machines (its synchronous generators), the proliferation of new loads with quite unfavorable dynamic characteristics is positioned (particularly, given the lack of understanding of their widespread operating effects) to soon dwarf and dominate the effects of the large generators. It is vital that a strong focus on discovery of these loads' full impacts be pursued. Yet, the "simpler" determination and communication of the metric describing particularly the grid's status for dynamic VAr adequacy or poverty is still needed, given the role that the synchronous generators still play today.

DOE therefore needs to effect discovery and communication of the world ahead, while at the same time acting as a catalyst for "remedial" discovery and communication! DOE is needed, among other reasons, because planning is usually conducted with unreasonable but well-defined deadlines set for achieving solutions. These short deadlines often limit planners' ability to reach for optimum solutions since justifying and implementing ideal solutions often require longer lead times. Even a return to synchronous condensers by converting generators at their very advantageous sites is quite complex as its cost swings greatly depending on "small" site details. Few planning departments have the bandwidth to pursue the tantalizing but elusive "best" plan.

PART TWO – Environmental Stakeholder Perspective

The Value of a VAr: Environmental Perspectives on Meeting Volt-Ampere Reactive Needs

Introduction

As noted in prior Electricity Advisory Committee (EAC) reports[16] the U.S. electricity delivery system is going through a major transition that is requiring extensive modernization. Many generation sources we have relied upon for decades for both energy and grid services are being retired for market, financial, and environmental reasons. These mainly baseload resources—particularly coal and nuclear plants—are being replaced by ever larger amounts of variable renewable energy sources and more flexible generation including gas-fired power plants able to ramp "real" power rapidly. As baseload plants with their substantial spinning mass exit the system, the need for ancillary services and especially voltage support (voltage-ampere reactive or VAr) becomes increasingly important and in some places acute. There are numerous options for providing VAr, but not all of them are available at every location such support is needed. Where they are available, new solutions, such as activating the reactive power functionality of inverters on distributed solar systems, have the potential to be powerful tools in replacing the need for spinning mass generators to provide VAr support. Currently systems rely on the generator connected to a turbine and its electrical excitation capability provides the VAr support. Conventional solutions may be controversial in some locations.

This section examines environmental perspectives on the need for providing VAr support to both the bulk and distribution electricity delivery networks in the face of rapid changes to the system, and suggestions on ways to do so. Regardless of one's perspective, a secure and stable electricity grid is an essential element in supporting our economy and public health system, and in fueling our everyday lives. The value of VAr is indisputable: it is a fact of life. There is no dispute that this grid service is needed in adequate amounts. There may be some disagreement about how to provide it in some circumstances. The hope is to create a consensus-building means of ensuring VAr support is available wherever it is needed to keep the system stable and ultimately reliable for all consumers. Will rigorously developing a portfolio of available options lead to easier public acceptance of the solutions?

What is Driving the Need?

Several factors contribute to the urgency of a VAr conversation. First, the electricity generation resources on which the grid depends are changing rapidly. Conventional coal plants are being retired for many reasons including market, regulatory, competitive, and public policy changes. Climate change concerns as well as national and state renewable energy policies have led to statutory and regulatory requirements that depress the use of fossil fuel generation, especially coal, and emphasize the use of zero-emission, variable renewable energy sources. These policies have helped create vast new domestic and foreign markets for renewable resources. The renewable energy industries—principally solar and wind energy—have scaled up manufacturing to meet escalating demand, creating economies of scale that have reduced costs and increased performance of renewable generation very rapidly. This rapid cost decline continues to drive deepening renewable energy

[16] DOE EAC, "EAC Recommendations on Expanding and Modernizing the Electric Power Delivery System for the 21st Century" (September 2014), see: http://energy.gov/sites/prod/files/2014/10/f18/ModernizingElectricPowerDeliverySystem.pdf.

penetrations into the U.S. electrical system and creates manageable but novel reliability challenges for grid operators. [17]

Simultaneously, demand for coal in developing countries is peaking and those markets are on the verge of steep decline, putting great pressure on domestic coal producers.[18] International commitments are keeping demand for renewable energy resources high and are expected to reduce capital costs for these resources further, which have no variable fuel costs. This lower-cost renewable power is applying competitive pressure to conventional energy generators that is rapidly changing the generation stack.[19] [20]

Gas Prices…Coal's Kryptonite?

Current low natural gas prices are also rapidly tilting the generation mix away from coal.[21] State compliance plans for meeting Clean Power Plan emissions reduction targets under §111(d) of the Clean Air Act are expected to feature deeper penetrations of renewable energy sources and natural gas generation to replace coal-fired power plants.

Merchant Nuclear Squeezed Out?

These same low fuel and capital costs for gas and renewable generation have likewise led to the retirement of merchant nuclear plants[22] and slowed any expectation of an expansion of these resources over a short-to-medium time frame. Nuclear plants, through their rotating turbine-generators systems, provide reliable VAr support in many locations on the electrical system. Nuclear plant retirements, depending on their location in the electrical system, may therefore require that location-specific measures be adopted to ensure adequate voltage support to the grid—as was seen with the retirement of the San Onofre Nuclear Generating Station in southern California. The sudden loss of this source of VAr required a blend of demand-side customer and technological measures to ensure an adequate level of local stability.[23] California's plan relies on a variety of tools to provide a mix of real and reactive power. It combines demand response, distributed generation, energy efficiency, electricity storage, converting gas turbines to synchronous condensers; transmission enhancements; and new and repowered gas generation to solve for system needs.[24] It does not rely on a single solution, but an amalgamation of many.

Another shift affecting the need for new sources of VAr includes the rapid customer adoption of distributed generation (mainly but not entirely solar photovoltaic [PV] systems). As distributed energy resources (DER) displace existing baseload generation in some locations in the system, the need for VArs may increase.

[17] See http://www.awea.org/MediaCenter/pressrelease.aspx?ItemNumber=7241 for a wind industry perspective on deep renewable penetration and system reliability.

[18] For news coverage of China's carbon reduction plans see http://nyti.ms/1bE04yQ.

[19] See http://bit.ly/1RlIRvc for information on China's changing energy portfolio.

[20] Domestic U.S. renewable energy prices are also becoming increasingly competitive. See November 23, 2014, http://nyti.ms/1GUmAwd.

[21] Natural gas prices are even depressing demand for Powder River Basin Coal, long thought to be resistant to competition from natural gas; see http://bit.ly/1ImWjwf.

[22] For news coverage on natural gas prices influence on nuclear power, see http://www.wsj.com/articles/SB10001424127887323854904578263952157252768.

[23] See http://bit.ly/1KSntcH for a description of the CPUC decision on SONGS replacement.

[24] The gas side of the solution relies on expected repowering of some turbines converting from once through cooling units and synchronous condensers. See http://bit.ly/1DX0NBS.

Fortunately, many DER inverters can provide voltage ride-through and frequency response as was recently demonstrated by Hawaii Electric Company (HECO).[25]

The net effect of these changes is that in many places generation that reliably provided VAr to the grid may no longer be available to do so. Instead of relying on the spinning mass generators, combinations of solutions will be needed to provide VAr. These may include advanced inverters and power electronics coupled with wind and solar installations where they are available,[26] [27] [28] and where they are not, replacement of coal generation with synchronous condensers and flexible gas turbines to keep the grid stable. Adding transmission and technologies such as clutches on gas generation facilities may provide voltage stability to the grid, if not VArs.[29]

Case Study: Hawaiian Electric Puts 800,000 Microinverters to Work…at Once

The HECO experience makes for a convincing case study of how a previously untapped attribute of a renewable energy system can be used to address a compelling reliability challenge.

In February 2015, HECO worked with microinverter manufacturer Enphase to successfully upgrade and activate 800,000 microinverters installed in distributed solar installations across Hawaii to provide voltage and frequency support to the grid. Enphase's systems are connected to an estimated 140 MW of peak power solar generation capacity in Hawaii.

Hawaii leads the nation in rooftop solar penetration. Approximately 51,000 customers, or one in nine households, contribute solar energy into the state's island power grids. There is a large backlog of households wishing to install solar panels on their homes and businesses. About three-fifths of existing solar systems use microinverters from Enphase, which have a two-way communications capability enabling the California-based company to remotely upgrade the inverters' software. Never before has such a large simultaneous inverter system reprogramming been done.[30] It was accomplished in one day. The reprogramming corrected an operational flaw in solar panel performance that occurred in low voltage events such as sudden loss of a generator or transmission line. Instead of forcing all affected solar units to shut down at once, making the original problem worse, they now have the ability to ride through such events and continue operating while the system recovers.

[25] For a description of how 800,000 solar module inverters were remotely programmed and activated see http://bit.ly/1DX14EY.

[26] American Wind Energy Association, "Wind Energy Helps Build a More Reliable and Balanced Electricity Portfolio," April 2015, p. 28.

[27] For a discussion of ancillary service solutions including VAr posed by deep renewable penetration into the electrical system due to Clean Power Plan compliance, see "EPA's Clean Power Plan and Reliability," Weiss, J., Tsuchida, B., Hagerty, M. and Gorman, W., The Brattle Group, February 2015, pp. 44 and 45.

[28] For an evaluation of both traditional and newer advanced power electronics voltage and grid support technologies see "Potential Mitigation of Dynamic Reliability Challenges with High Levels of Variable Energy Resources," Lew, D., D'Aquila, R., Miller, N., GE Consulting for Western Interstate Energy Board, April 24, 2015, pp. 5-15 to 7-17.

[29] Ibid at p. 5-13. "In order to provide voltage support and inertia while the gas plant is shut down, a clutch could be installed that allows the generator to continuously spin, despite the fact that the gas turbine may be shut down. Clutches are not new (for example, the Los Angeles Department of Water and Power, LADWP, has clutches on two of their gas plants) but they are not very common."

[30] "Specifically, Enphase and Hawaiian Electric have reset the frequency and voltage ride-through settings of the microinverters, which govern how and when they trip offline when grid fluctuations arise. Standard settings for low-voltage ride-through (LVRT), however, can make the original disruption worse if it leads to a majority of the solar being supplied to a solar-heavy circuit to shut off all at once." See http://bit.ly/1EppTKn, Greentech Media, February 2015.

Enphase microinverters can now provide reactive power but this added functionality has not been universally activated. California adopted ambitious smart inverter standards in 2015.[31] The California Independent System Operator is presently promulgating a policy that would require and compensate all new, large, grid-connected solar projects for providing reactive power to the system using their inverter capabilities.[32] This proposal also recognizes, as does a new policy at PJM, that sizing larger inverters to ensure that sufficient VArs are always available does come at a cost, and that this cost should be compensated.

The speed and flexibility of inverters make them ideal for dynamic VAr provision, which in turn makes them ideal for FIDVR mitigation. The key to this benefit is the implementation of effective control methodology. For FIDVR, the latency of central control can limit performance. A control scheme in which inverters respond dynamically and autonomously to disturbances in accordance with dispatched control set points may be more effective. In addition, the location of the resources is also of great importance. It is most efficient to provide VArs where they are needed. Other details such as their location on a feeder or their location relative to a tap-changing transformer can limit their benefits. Carefully analyzing system needs and strategically locating these tools is becoming recognized as an important element to reliably introducing large amounts of clean energy into a stable and reliable electrical system.

These are game-changing developments for distribution grid management and reliability.

Scratching the Surface of What's Possible

The full potential of advanced power electronics, including inverters that provide the grid interface for energy storage, is still being explored, although great progress is being made. NERC has found that wind turbines have the capability to provide many grid-related services. Through their active and reactive power control capability, wind plants can provide both frequency and voltage response, including inertial response, voltage and frequency ride-through, and other grid reliability needs.[33] As we have seen, the power electronics used on solar generation, wind generation, and energy storage can provide critical grid services that are presently underutilized. Some of these attributes are available in many places now. Some will be available soon. VAr support is not considered in isolation as these tools become increasingly available, but is one of a number of grid support services being provided by these technologies. The key to making them routinely available may be the development of market products that compensate providers for these grid services.

A Key Question: Which VAr Solutions Are Available at the Given Locations Where Need Arises?

VAr solutions can be very different from one place to another. For example in utility service areas with deep penetrations of renewable energy generation, advanced power electronic inverters can play a major role. In locations where these resources are less available and where coal plant retirements may result in greater VAr

[31] The Smart Inverter Working Group (SIWG) grew out of a collaboration between the CPUC and California Energy Commission (CEC) in early 2013 that identified the development of advanced inverter functionality as an important strategy to mitigate the impact of high penetrations of distributed energy resources (DERs).The SIWG has pursued development of advanced inverter functionality over three phases. Phase 1 considered autonomous functions that all inverter-connected DERs in California will be required to perform. Phase 2 considered the default protocols for communications between IOUs, DERs, and DER aggregators. Phase 3 is currently considering additional advanced inverter functionality that may or may not require communications.

[32] CAISO's proposal, "Reactive power requirements and financial compensation," which requires FERC approval can be found at http://bit.ly/1Ie8OL4.

[33] See http://www.nerc.com/files/ivgtf_report_041609.pdf, p. 22, "As variable resources, such as wind power facilities, constitute a larger proportion of the total generation on a system, these resources may provide voltage regulation and reactive power control capabilities comparable to that of conventional generation. Further, wind plants may provide dynamic and static reactive power support as well as voltage control in order to contribute to power system reliability."

shortages, more conventional solutions may be needed, including gas turbine clutches, synchronous condensers, SVCs, or STATCOMs, perhaps in some combination. Energy storage might play a role in almost any circumstance. In still other situations, however, transmission enhancements and VArs from gas turbine generation may be the best or only choice to provide voltage stability.

The essential point is that solutions will inevitably be tailored to meet local needs and conditions, and those solutions will depend on the array of technologies available at each location. Both the type (static or dynamic) and amount of VAr needed will guide the selection of the suite of solutions grid operators and utilities will choose.

Selecting a Portfolio – the Key to Stakeholder Buy-in?

From an environmental perspective, low- or zero-carbon solutions are preferable to traditional VAr options when they are available. Given the overarching need society has to decarbonize the electricity sector to address climate change, and the continuing need in many parts of the country—from urban areas to rural communities where new sources of criteria pollutants are giving rise to deteriorating air quality[34]—adding new sources of fossil fuel emissions may not be a viable option. Environmental and consumer stakeholders have already been critical of fossil-fueled solutions when others are available.[35]

As mentioned above not all solutions will be available at every location. But a key to avoiding opposition will be making the case that the preferred set of VAr solutions considered are those that include the best range of environmentally preferred approaches to meeting the VAr need.

Finally, DOE has helped support the development of emerging Volt-VAr control technology that uses power electronics on the edges of the distribution system to equalize voltages across secondary distribution lines. This new approach has been demonstrated to reduce demand and energy requirements by 5 percent or more, maintain standards compliance, and expand the ability to host distributed PV. Such systems combine a distributed communication and control architecture with sensors, VAr sources, and smart inverters located on secondary distribution lines that have real-time communication capabilities and access to the required control algorithms. Broader awareness of these systems could provide significant cost savings, improve system reliability, and facilitate compliance with environmental requirements.

[34] For an overview of air emission issues related to unconventional oil and gas development, see "Fracking Fumes: Air Pollution from Hydraulic Fracturing Threatens Public Health and Communities," Srebotnjak, T. and Rotkin-Ellman, M., NRDC Issue Brief, December 2014, at http://bit.ly/1KrS3ZF.

[35] One such example is the proposed Carlsbad gas plant in southern California; see http://bit.ly/1F4MUqy.

PART THREE – Policymaker Perspective

The Value of a VAr: Challenges and Questions for State Policymakers

This section focuses on issues that are important for state policymakers to understand about the value of VAr. At a recent 2015 DOE meeting on transmission in Denver, Colorado, a 30-year executive with a major U.S. utility was asked what he thought were the major policy questions around the loss of endemic VAr. His answer was that he has had his electrical engineers explain this to him over his thirty years in the electricity sector and he still does not understand it.

The complexity of understanding VAr and its value, if difficult for the seasoned electricity professional, will be a monumental challenge for many of the citizen legislators of the United States. Further, understanding why policymakers need to raise constituent rates to pay for something that their constituents or ratepayers were getting for free will be even a larger challenge.

Recognizing Diffused Regulatory Structure at State Level

It will be critical for DOE to realize how the structure for regulating electricity is trifurcated at the state level. Many state legislatures have delegated legislative authority for regulating rates of private utilities to public utility commissions (a handful did this in their constitutions when brought into the Union.) State legislatures have also passed some local regulation of rates onto elected governing boards of public utilities or non-profit cooperatives. The sale, monetization, or regulation of values outside of Kwh has to be expressly authorized by statutory law in almost all cases for public utilities.

Integrated Resource Planning Is a Keystone

Thirty-three of the states require integrated resource planning (IRP) as a precursor to generation resource procurement (see Figures 4a and 4b). Most of these are required by public utility commissions of private utilities and run the range of least-cost (least-fuel cost) to life-cycle risk with an efficient frontier economic modeling. A few states require private and public utilities who are procuring new generation resources to all conduct a full life-cycle risk IRP process.

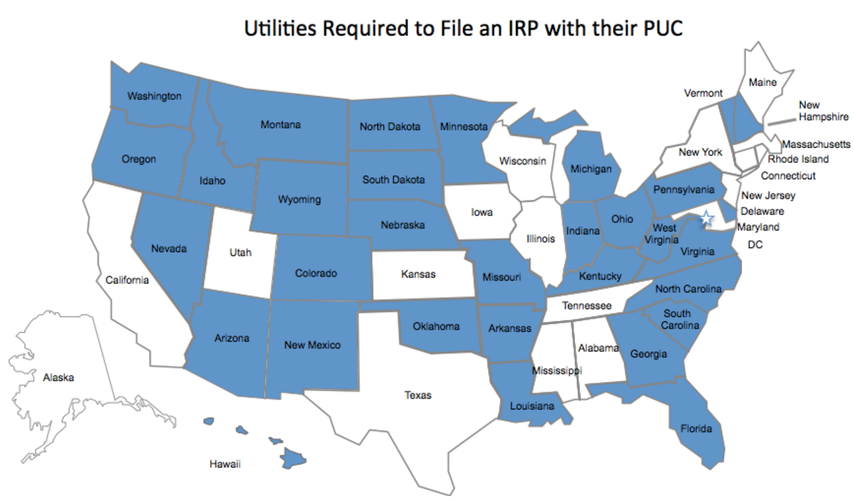

***Figure 4a**: States that Require Integrated Resource Planning as a Precursor to Generation Resource Procurement.*

The IRP process provides transparency to generation resource choices and presents complex economic risk choices in a digestible form for all types of stakeholders. Whether it be a simple least-cost fuel source IRP or a complicated efficient frontier IRP process, both normally use the Monte Carlo analysis to compare different potential resource portfolios. Stakeholders then bring their vantage points of what has been valued poorly to bear on a final projected procurement portfolio.

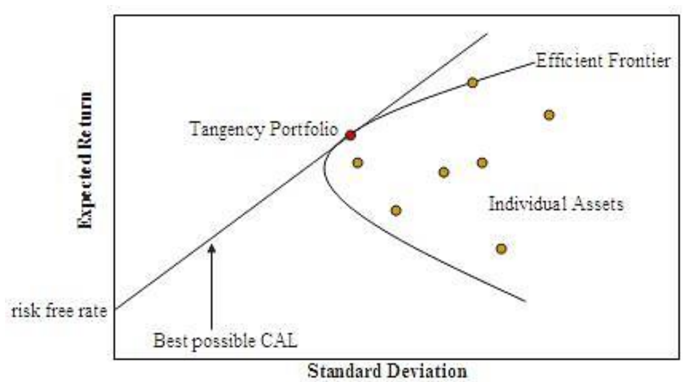

***Figure 4b**: The Efficient Frontier Model*

Currently VAr is not valued in IRPs because it is either not recognized as existing at all, or divorced from generation altogether and put into an ancillary services silo. While siloed VAr might be monetized in the form of shunts or capacitors, many of these are one-off backstops and are never compared or valued in the IRP process since it is provided endemically today.

DOE would be well suited to produce standardized monetized values for VAr associated with different generation technologies, and this would provide a great deal more understanding and transparency of the value of VAr. This would allow communication to policymakers and stakeholders about the alternative costs available to provide VAr within the mosaic of IRP processes.

Clean Power Plan Is Retiring Capacitive VAr

Another distinction on which the states need to make a conscious choice is the question of inductive versus capacitive VAr.

As EPA moves forward with the Clean Power Plan and starts to remove coal generation facilities that have been providing VAr for free, or as the previous section's *"froth on a mug of beer"* graphic depicts, it will be critical to communicate in a simplistic way the importance of VAr to reliability as well as the difference between leading and lagging VAr to an existing electric grid.

Some presumption exists in previous sections that DER and accompanying smart inverters will provide VAr support. It is important to note that the default policy decision is that when swapping out a free leading VAr resource for a lagging VAr resource, individual customers or rate classes of customers (like owners of distributed generation or electric vehicles) should pay on the distribution side of our electric system.

It is not clear that distribution VAr in any way will support reliability of the high-voltage transmission system; or that peaking single cycle gas turbine (SCGT), shunt capacitors, shunt reactors, SVCs, or any other voltage control devices, be they on the high voltage or distribution side of the system, should be socialized among all customer rate classes.

Lessons Learned from Past Policy Experiences

An opportunity missed in the past for states that passed renewable portfolio standards (RPSs) was to have only allowed renewable resources to consumer markets and RPS compliance that brought 100 percent firm resources. Again, if this option had been adopted early much greater transparency of the color and cost of RPS-compliant generation would have resulted.

A similar moment in time is before us with VAr. If new generation resources coming to market were required to provide the same type of VAr availability that is currently enjoyed in the generation resource fleet, a much more transparent picture of the cost of competing generation technologies would occur.

The barrier to this choice is lack of understanding of the value of VAr in federal and state mandates. Requiring provision of these monetized values as part of compliance with existing mandates would go a long way to understanding that VAr has value.

Why Should States with Renewable Resources Hold the Bag of Cost for VAr?

The Western Governors Association (WGA) recently completed a Western Renewable Energy Zone (WREZ) assessment. One of the outcomes of the assessment was to show that existing transmission was sited nowhere near many of the renewable resources in the Western United States.

That study also begs the question: if renewables are built in state jurisdictions with abundant renewable resources for the purpose of export to other jurisdictions, do the mechanisms exist to recover the costs of the peaking SCGT, shunt capacitors, shunt reactors, SVCs, or any other voltage control devices in the high-voltage wholesale markets so that ratepayers in the host renewable states are not left holding the bag for costs of providing VAr in a post-EPA Clean Power Plan era?

Summary

DOE will not only need to educate legislators on the value of VAr, but also to provide them with tools to communicate with their constituents why VAr needs to be paid for, and about the range of policy options on who should pay and how.

PART FOUR – Regulator Perspective

The Value of a VAr: Strategies for Advancing Regulatory Policies to Address Volt-VAr Challenges on the Power System

Introduction

Voltage regulation is essential for maintaining the reliability of the transmission grid and distribution system, but the engineering and technical aspects are not very well understood by public officials and economic regulators. The transmission and distribution grid delivers both real power and reactive power to end-use consumers that results in voltage drops and line losses. Ideally, to optimize the grid one would like to deliver real power to the users while minimizing line losses and decreasing voltage drops. However, motors, fluorescent lighting ballasts, compact fluorescents bulbs, LED bulbs, computers, and cell phone chargers require reactive power to operate. Most power meters measure real power (watts) only. Reactive power demands result in increased currents on our grid that significantly increase losses and result in voltage drops at the ends of the distribution system.

The measurement of real power consumption (watts) underpins much of the rate regulation methodologies employed by economic regulators to assign system cost responsibility to various classes of customers. In contrast, the need and role of reactive power is less visible, but it remains as an equally critical component of system reliability. This is partially due to the fact that the reactive power needs of most customers on the distribution system are typically not measured, recorded, and billed to customers. Thus, at the distribution level, the local utility usually socializes the cost of reactive power to all of its customers. However, utilities require large industrial users to have power meters that measure real power and reactive power so they can be billed for the reactive power. Large industrial customers utilize capacitor banks to reduce their reactive power requirements to realize cost savings.

At the transmission level, the system must have an adequate amount of generation for both real power and reactive power to maintain acceptable voltages under both “steady state” and contingency conditions. In vertically integrated areas, the system operator may enter into purchase power agreements for the provision of reactive power. In those regions that have restructured, and now utilize regional markets, reactive power needs are typically procured through “ancillary” markets (although these “markets” are typically “tariffs” for providing some level of cost-of-service recovery, rather than “cleared” markets, due to the difficulty of specifying the service in a manner that it can be procured through a uniform clearing price auction).[36]

A number of industry and market trends have highlighted the growing importance of reactive power. First, with the increasing retirement of large, conventional base-load power plants resulting from new environmental regulations, coupled with the increasing penetration of renewable generation, the level of reactive power support from generation has entered a gradual decline in some power systems. Secondly, as states enact policies to promote the development of low-carbon, distributed energy technologies such as customer-sited solar PV, the intermittent generation and the corresponding bi-directional flow of power to and from those facility locations can have direct and significant impacts on the voltage stability of the system. Further compounding the problem is the constant addition of power electronic devices by consumers who require increasing amounts of reactive power.

[36] See the paragraph associated with footnote 40 for related material.

Fashioning policies to address the growing need for reactive power in light of the increasingly dynamic events challenging the power system is no easy feat. The power system itself is incredibly dynamic.. The system faces a number of small disturbances all of the time—changes in load, generation, ambient temperature, etc. The voltage stability challenge that reactive power overcomes relates primarily to the ability of the system to maintain stable bus voltages following a disturbance or a deviation from an initial operating condition. The reactive power needs of the system can be satisfied from three different sectors: (1) bulk-power system generators that have the capability to generate spinning reserves; (2) distribution utilities that can deploy synchronous VAR capacitors (SVCs and STATCOMs) or line capacitors; or (3) end-use customers by either requiring or incentivizing the VAR production from interconnected devices at a specific customer location. Although any combination of these three VAR production sectors would achieve necessary voltage support and system reliability, the larger question remains—what is the most cost-effective strategy?

As described further below, it is the EAC's assessment that DOE can play an important role in educating state public policymakers about the importance of voltage regulation so that states can formulate the most cost-effective approaches to developing distributed generation on the utility systems while also adopting policies that provide for the optimum level of voltage support depending upon the locational needs of the system. Optimum levels of voltage support can reduce system losses, increase circuit capacity and increase reliability, all of which improve the efficiency of the overall distribution system.[37] Further, it is the EAC's assessment that DOE can play a similar role where federal public policymakers are concerned.

The Growing Problem of Voltage Instability

Increasing penetration of distributed generation along with its intermittent power characteristics, can decrease system inertia, compromise voltage stability and result in frequency aberrations. Voltage stability refers to the ability of the power system to maintain stable bus voltages following a disturbance or deviation from an initial operating condition. Intermittent power flows on the system, and the ensuing fluctuations across buses, could potentially trip circuits and cause local or system-wide load loss. It can also degrade machine synchronism and thereby cause rotor angle instability. A second serious outcome of voltage instability, which can otherwise be described as upsetting the equilibrium between load demand and load power supply, is called voltage collapse. Voltage collapse is a product of severe voltage instability, and in particular relates to low voltages that exceed transformer capabilities. Although there can be several contributing factors leading to voltage collapse, load fluctuations are typically the driving factor and are characterized by small system disturbances and large system disturbances. In either case, high penetrations of distributed energy technologies (e.g., solar PV) can exacerbate demand fluctuations and increase the likelihood of a voltage disturbance event, which can be of either short term or long-term duration (ranging from seconds to minutes).

What Regulators and State Policymakers Need to Know

Voltage challenges can be addressed by a number of technical solutions. One approach is to increase reactive power support in areas of depressed voltage by adding generation with dynamic reactive capability, or adding distribution feeder capacitors, substation capacitors, synchronous condensers and dynamic reactive devices. An alternative approach is to decrease reactive power losses in the network by adding capacitors in series or by system solutions, for example STATCOMs and superconducting magnetic energy storage (SMES).

[37] See "A Tariff for Reactive Power," Oak Ridge National Laboratory, ORNL/TM-2008/083 (2008).

For utility system planners and regulators that must approve rate recovery of system investments, the ability to project peak load in areas that are expected to have high penetrations of distributed solar power generation becomes critical. Failure to anticipate the level of distributed generation penetration on the system can, at best, lead to inefficiencies in the design and build-out of the distribution system, and at worst lead to potential outages and compromised reliability. The question remains, what is the most optimum method of addressing the reactive needs of the system, particularly given that the voltage stability challenge seems to be accelerating at the fringe of the distribution system due to increasing penetration of customer-owned devices such as PV systems, micro-turbines, fuel cells, compact fluorescent lighting, LED lighting, variable speed motors, etc.? The distribution service operator will typically respond to the voltage challenge by adding capacitors such as SVCs. While the addition of capacitors can provide reactive power to boost voltage, their capability drops significantly as the voltage drops on the system.[38] Given the dynamic nature of reactive power requirements at the fringes of the distribution system, capacitor banks are subject to frequent switching and thereby lead to premature equipment degradation and costly maintenance.

At the other end of the spectrum, and literally at the edge of the distribution system, there are broad opportunities to secure reactive power from inverter-based equipment such as PV systems, fuel cells, micro-turbines, etc. According to a study conducted by the Oak Ridge National Laboratory (ORNL), the provision of time-varying reactive power from inverter-based equipment depending on real-time voltage conditions on the system can be the most economic and reliable method for procuring reactive power. Reactive power from customer-owned devices is referred to as dynamic reactive power or “dynamic VAR production.” ORNL projects that customer-delivered reactive power can be produced for as low as $5 per kVAr when the value to the distribution system is estimated at $7 per kVAr (including reduced losses, increased line capacity, and transfer capability).

However, there are a number of pragmatic limitations that currently impede such an approach. First, the window of opportunity to secure dynamic VArs from a customer is very narrow. As customer needs evolve and equipment is changed out, customers can be informed about the opportunity to provide reactive power. According to ORNL, the use of a “VAr tariff” could incentivize customers to design and invest in systems that can provide reactive power at a cost less than the value of the provided service. With advanced warning and a fair opportunity to be compensated for equipment upgrades that can help achieve distribution system requirements, such an approach has the potential to decrease the cost of reactive power at the system level while freeing up line capacity and transfer capability, and thereby improving overall reliability.

Another approach could be for distribution service operators to provide financial incentives to customers to purchase the best available equipment, systems, or devices that would minimize system disturbances and/or provide adequate reactive power capability. This approach would be similar to energy efficiency programs that seek to engage customers and incentivize purchases of more efficient devices, equipment, and systems. Similar to energy efficiency programs, however, there is a comparably small window of opportunity to ensure that customers are compensated to make decisions that benefit themselves as well as the efficiency of the entire system. Regardless of the approach, success will be highly dependent on a strategic assessment and modeling of the system to ensure that any program is cost-effective based on the locational value of procured resources.[39]

[38] The effectiveness of solid-state capacitor devices such as SVCs is proportional to the square of the voltage. Thus, as voltage drops, the impact of the devices drops significantly until voltage collapses.

[39] This paragraph links to the material associated with footnote 37.

Creating a market approach to securing dynamic VArs appears impractical because the actual voltage requirement is so localized that any market zones would have to be small and the computational process quite complex. At the other extreme is an approach adopted by the California Independent System Operator (CAISO), which simply mandated that all PV systems connecting to the grid possess specified inverter capabilities to produce or absorb VArs by maintaining a minimum power factor range. However, this may not be the most efficient approach since the prescribed capabilities do not necessarily reflect local power system requirements or acknowledge differences in the reactive power delivery capability of the actual inverter.

Recommendations for DOE Action to Advance Volt-VAr Policies

As the preceding discussion illustrates, there are a number of considerations that planners and policymakers must undertake to advance sensible policies for securing reactive power at the distribution level. The chosen policy decisions will ultimately have direct repercussions on the overall efficiency and reliability of the electric power system. The EAC believes that DOE can play a pivotal role in the policy formation process, and recommends the following suggested actions:

(1) Engage national laboratories like ORNL to continue researching and assessing available technologies for reactive power along with providing an assessment of the overall cost-effectiveness of competing approaches;
(2) Educate regulators and policymakers about the importance of reactive power on distribution systems by partnering with the National Association of Regulatory Utility Commissioners (NARUC) and hosting technical conferences and webinars;
(3) Further evaluate the need for equipment manufacturing standards for PV systems, variable speed motors, lighting, electronic devices, etc.—where revised standards can provide electric system efficiency and improved reliability;
(4) Assist in the development of load models that will help utilities forecast system requirements; and
(5) Assist policymakers in understanding which reliability services will need to be procured, particularly as related to the implementation of renewable energy programs that are pursued in response to federal and state mandates.

CONCLUSION

The four perspectives presented can be distilled into fairly simple terms:

- The grid planner says, "Maintain grid reliability at all cost—resist anything that might threaten it."
- The environmental stakeholder says, "Use every available low carbon option to provide VAr as we plan the grid's evolution—externality costs[40] should be factored into large decisions."
- The policymaker says, "Educate me and help me explain to constituents why costs have to rise; reactive power that used to come free will now have to be monetized and incorporated into rates."
- The regulator says, "The grid is increasing in complexity and a suite of solutions is available from which to mix and match to mitigate emerging problems. I need to be educated in order to ensure that I approve the optimum solution set(s) and build it/them economically and fairly into the rates that I govern."

Having now explored the topic of the value of a VAr and perspectives on electric grid voltage support from four important perspectives, who then will play the part of the omniscient fifth person that pulls these threads together? The EAC believes this answer to be obvious.

Each of the four perspectives pressed a similar case for needing DOE to act in a leadership role going forward. At the same time, it would have been hard to miss in each narrative the veiled and even explicit references to the leadership and catalytically vital role that DOE has already played to the benefit of all. DOE has moved the grid and its stakeholders forward in understanding and performance through its research, development, demonstration, and communication efforts. DOE has partnered well with the industry, national labs, and other appropriate groups.

While each focuses on issues that are a bit different since they are seen from different value sets, the requested actions from each perspective are not in conflict with each other. Rather, together these requests flesh out a synergistic body of work that the EAC approves and by transmittal of this paper requests DOE to provide.

[40] Externality costs include health costs avoided by moving the resource mix from high emitting to zero or low emitting technologies. Policies now differ on whether or how these should be considered.

APPENDIX A

What Is a Volt-Ampere Reactive?

In any electrical circuit the power consumed is the voltage (unit volts, written V) multiplied by the current (amperes, A). The unit of power is then volt-amperes (VA). In direct current (DC) circuits, this power (VA) is also called watts (W), which over time is the work done or energy consumed. But in alternating current (AC) circuits the power (VA) has two components: the first is sometimes called volt-amperes-real but more often called watts (W) as this is the same power that does work like in the DC circuit; the other component is called volt-ampere reactive (VAr) but this component of power does not do real work (consume energy).

In AC circuits the voltage and current alternates (oscillates) at 60 cycles per second (60 Hertz, Hz). In Figure A-1, two cycles of an AC voltage (blue line) and an AC current (purple line) are shown; note that the voltage and current are 'in phase' which means that the oscillations peak and cross zero at the same time. The red line is the power obtained by the voltage multiplied by the current; note that it oscillates at twice the frequency (120 Hz) and is never negative. As this is the trace of the power over time, the area underneath the red line is the energy consumed. If the area is divided by the time, the value obtained is the average of the red oscillation (shown by the dashed red line) and this is the real power in Watts (there are no VArs in this case).

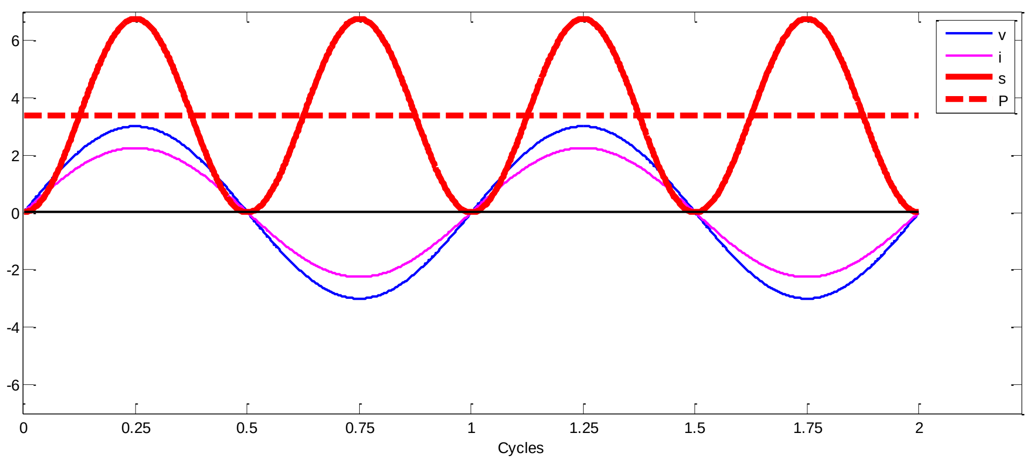

Figure A-1. *Power in an AC circuit when voltage and current are in phase.*

However the voltage and current may not always be in phase, and Figure A-2 shows the case where the current lags the voltage in time by a quarter-cycle (also known as 90^0 because one cycle is denoted by 360^o) which means that the current peaks a quarter cycle after the voltage. The power curve is still oscillatory but is as much negative as is positive. In fact, the area under the curve is zero because the positive and negative parts cancel out. The energy consumed is zero and the average power is denoted by the zero line. However, there is obviously some power that is oscillating and a measure of this oscillating power is given as the reactive power in VArs (there are no watts in this case).

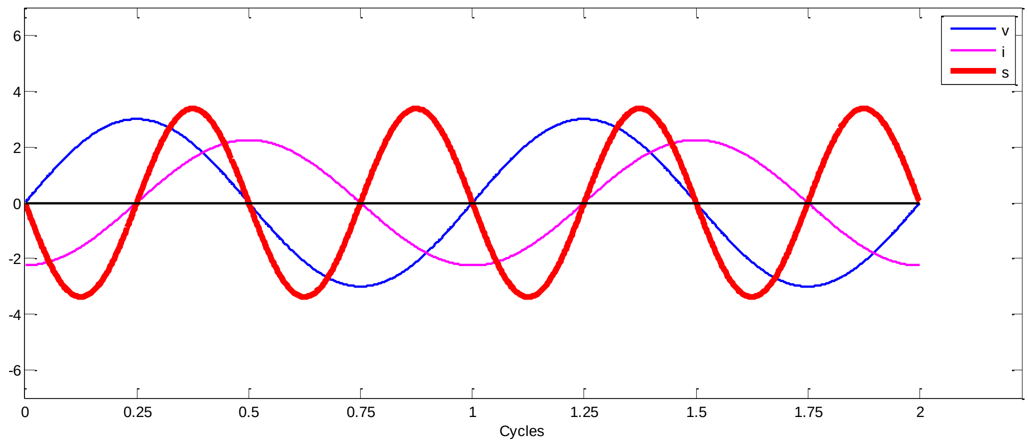

Figure A-2. *Power in an AC circuit when current lags voltage by quarter of a cycle.*

Figure A-3 shows a case in between Figure A-1 and Figure A-2 where the current lags the voltage by one-eighth of a cycle, i.e., the current peaks 45^0 after the voltage. The oscillating power is shown with a positive average; as explained before this is the real power in watts. If this average power is subtracted from the oscillating power, the result is the green oscillation with an average of zero. This green oscillation then must represent the reactive power in VArs. Thus, in general AC circuits consume both real power and reactive power except in the two special cases: when reactive power is not consumed because the voltage and current are in phase, and when real power is not consumed when voltage and current are 90° out of phase.

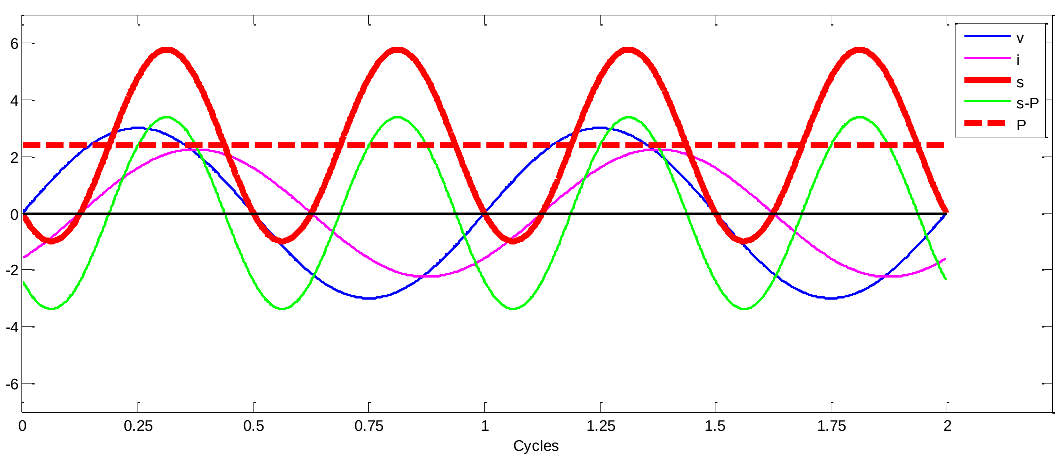

Figure A-3. *Power in an AC circuit – general case.*

When currents flow in wires they set up electric and magnetic fields, which can store energy in electrical equipment such as electric coils or capacitors. All transmission lines, cables, transformers, etc. behave like coils and capacitors so the grid can store a lot of energy. Moreover, because the current alternates, so do the electro-magnetic fields thus charging and discharging the stored energy. This stored energy in an AC circuit is oscillating, so cannot be used to do actual work and forms the second component known as VArs. Why do we care about VArs if they don't provide us with energy? Because the circuits (of the grid) have a certain capacity of carrying power, this reactive component takes up some of that capacity because it oscillates, so we need to calculate and measure it. Further, even though the VArs don't provide energy they have a significant effect on the voltage, which has to be controlled quite closely.

APPENDIX B

Load Modeling and Load Research Opportunities

To avoid equipment damage and blackouts, customers need reliable voltage support. A challenge in system planning is ensuring customers have the reactive power they need for voltage support when we often don't know what their loads will be or where their power will be delivered from.

Generation Retirement and Dispatch Flexibility Considerations

Watts and VArs differ like dogs and cats when it comes to travel. Hanging his head out the window will incur some resistance, but the dog will get to your destination intact (as will watts). Conversely, cats and VArs just don't travel well.

Reactive power is needed locally not only to serve the customers' loads, but also to supply the reactive losses incurred on lines and transformers due to their power deliveries. For this reason, most existing generation was located geographically close to customer loads, or electrically close to them through strong transmission corridors. As a general rule, if generation retirements or other changes in generation dispatch result in an area not having local generation sources on a temporary or permanent basis, some form of replacement voltage support must be provided reasonably close to the customer loads. Retirement studies must assess not only which generators are being retired, but also where replacement generation will be located.

Transmission planners understand that a local generator that is fully capable of supplying local customer loads cannot simply be replaced by an identical generator located somewhere else. This is because power traveling on transmission lines creates both real power losses (watts) and reactive power losses (VArs). Losses are a factor of distance, the size and configuration of the wires (bigger conductors are better), and the *square* of the current flowing through them. High voltage lines enable power to be delivered at lower current levels compared with low voltage lines; therefore, losses are lower for high voltage lines, other factors being equal. Both types of losses increase very quickly as power deliveries (current flows) increase, but the reactive power losses (VArs) can be as much as 10 times as large.

A line delivering 1000 MWs with only 10 MWs of real power losses may have reactive losses of over 100 MVArs.

Real power losses require that additional power be generated to serve customer loads due to resistive heating losses during delivery. Reactive power losses on a line result in steadily lower customer voltages, up to a critical point where customer voltages will collapse.

Customer power delivery and voltage support needs can be met by building high voltage transmission corridors to supply the replacement generation, if the new resource locations are known. These investments can be expensive ($millions per mile) and typically require significant lead time (5-10 years) to determine siting, gain approvals, and acquire rights-of-way. If replacement generation locations are not known, or if sufficient lead time is not available, local approaches may be necessary. Local approaches for voltage support are often more economic.

Customer voltages can be supported locally by building a combination of both static (less expensive) VAr sources like shunt capacitors, and dynamic (more expensive) VAr sources like generators, synchronous condensers, and power electronic based devices. The challenge of reactive compensation is ensuring sufficient dynamic range such that local voltages are not too high during low customer load periods, and not too low during high customer demand periods. Some of the reactive power sources must provide dynamic reactive reserves that are available at all times to be quickly deployed in the event that an unexpected line outage suddenly increases power flows on the remaining lines with a corresponding sudden increase in reactive losses. Static and dynamic VAr sources can typically be added within or adjacent to existing facilities with two to three years' lead time. It should be noted that voltage support is not the only essential reliability service needed to support customer loads. Good reference materials are available from NERC on voltage support, frequency response, and other ERS.[41]

"It's tough to make predictions, especially about the future."

Knowing customer loads is essential to performing reactive planning, but the magnitude and composition of customer loads are constantly changing throughout the day, with each season, and into the future. Customer loads are composed of both real power (watts) and reactive power (VArs). Current trends show customer load compositions shifting away from resistive type loads that consume only real power (strip heat, incandescent lighting, etc.) toward loads that consume both real and reactive power (heat pumps, LED lighting, etc.). This trend is placing additional focus on assessing emerging transient issues, as discussed in the section earlier in the paper, "Emergence of the Fault-Induced Delayed Voltage Recovery Issue Requires Dynamic Voltage Support for Mitigation."

Transmission planners assess voltage support needs for both steady-state conditions and transient conditions. Steady state is when the power system is not experiencing temporary disturbances such as faults or switching. Transient is what occurs during the brief transition which occurs during unexpected disturbances before the system has settled back into balance.

Steady-state load models can be reasonably developed from customer metering data and economic forecasting. Nonetheless, steady-state modeling is complex and resource intensive. Emerging challenges in steady-state modeling include distributed generation, which may mask portions of customer loads, and seasonal customer equipment, which may behave significantly differently during certain periods in the year.

For example, heat pump and air conditioner loads are motor loads during summer which saturate at around 95 degrees and do not increase significantly even if temperatures continue to climb. Conversely, below 32 degrees, heating may transition to resistive loads, and continue to increase dramatically as temperatures drop farther and farther.

Transient load models are based upon differential equations, and the parameters cannot be developed from customer metering data. Transient load models evolve through an iterative process of generic modeling coupled with benchmarking of actual system events. Developing transient load models is challenging due to customer load compositions' changing continuously throughout the year, system faults for benchmarking being

[41] NERC, "Essential Reliability Services Task Force Measures Framework Report," http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSTF%20Framework%20Report%20-%20Final.pdf.

unpredictable and infrequent, and benchmarked events not occurring during the load periods of interest. Transmission planners address these events.

Significant industry research at Electric Power Research Institute (EPRI) and in academia continues in pursuit of techniques to develop and benchmark transient load modeling without dependence on system faults. The holy grail of load modeling would be a “black box” that could develop load models while the system is in a normal operating state. Good reference materials are available through EPRI and other sources on load modeling research.