Assessment of Proposed CEIDS R&D Project on Power Electronics-Based Controllers

Prepared for the Steering Committee of the
Consortium for Electric Infrastructure to Support a Digital Society (CEIDS)

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Preface: Background and Purpose of This Document

At the initial meeting of the Steering Committee for the Consortium for Electric Infrastructure to Support a Digital Society (CEIDS), the power electronics-based controllers area was identified as a critical technology for the power delivery system of the future**.** At that meeting, the Committee proposed that CEIDS undertake a scoping study on post-silicon power electronics. The resulting EPRI scoping study on post-silicon power electronics showed that a tremendous amount of work was currently underway in this area and that CEIDS could not substantially accelerate the development of post-silicon materials. The CEIDS Steering Committee agreed with the recommendation not to pursue work on post-silicon power electronics.

However, due to the importance of power electronics-based controller technology in general, the Committee recommended that CEIDS conduct a scoping study to identify needed R&D in the area of power electronics-based controllers. The resulting study, developed by Dr. Aty Edris and Dr. Laszlo Gyugyi, was presented at the August 2002 Steering Committee meeting. The study recommended specific R&D projects that complement the work of others and would eliminate key barriers to widespread adoption of power electronics-based controllers.

The Steering Committee agreed to advance this work to the next step by forming a public advisory group (PAG) and preparing information for a business analysis. In November 2002, the PAG reviewed and endorsed the project plan. In early 2003, questions were raised regarding the proposed R&D, resulting in the need for additional information about the proposed work. This paper provides the requested information on power electronics-based controllers and the proposed CEIDS R&D project in this area.

Introduction

Over the past two decades, significant technological progress has been achieved in the development of solid-state, power electronic-based transmission and distribution (T&D) controllers and systems, which enable a degree of precise, high-speed control of electricity flow on utility grids that is analogous to that afforded by microelectronics in computers. But despite the technical success thus far, power electronics technology is at a critical crossroad. The initial technology, based on silicon thyristors (or silicon-controlled rectifiers) in various circuit and device configurations, is relatively mature and standardized among major electrical equipment manufacturers. However, the technology is also costly and offers limited technical capabilities to address the breadth of T&D challenges.

At the same time, emerging, new power electronics technology based on voltage-sourced converters promises a much wider range of functionality and applications and offers the potential to reduce the complexity, size, weight, and cost of highly sophisticated, multifunctional controllers for T&D systems. Today, reliability, availability, performance, and cost barriers limit adoption of this more promising type of power electronics-based controllers.

Value Proposition:

Power electronics technology based on voltage-sourced converters (VSC) offer a much wider range of functionality and applications than thyristor-based power electronics devices now in wide commercial use. Application of VSC-based devices will enable utilities to defer or avoid construction of new transmission lines, relieve transmission bottlenecks, avoid transmission line relief, and realize other benefits. At the same time, R&D needed to enable widespread adoption of these devices will reduce their costs and enhance their reliability, compared to their predecessors.

The purpose of this paper is to provide the CEIDS Steering Committee with background information to help evaluate the importance and value of the proposed CEIDS initiative on power electronics R&D. The purpose of the proposed R&D is to enable widespread adoption of the new voltage-source converters in a variety of transmission and distribution applications. This document will address the following key points:

- Widespread adoption of power electronics-based controllers is necessary for the attainment of the CEIDS vision.
- *Converter-based* power electronics controllers are a necessary component of the power delivery infrastructure of the future.
- Widespread adoption of *converter-based* controllers will provide opportunities to solve a much wider range of problems because of their diverse application potential and greater functionality.
- Proposed CEIDS power electronics-based R&D is needed for the advancement and widespread adoption of converter-based controllers.
- Proposed CEIDS power electronics-based R&D complements the work of others and is part of a larger effort to advance power electronics-based controllers in general.
- Other parties are unlikely to conduct the proposed CEIDS power electronics-based R&D.

Realizing the CEIDS Vision

Simply stated, today's power delivery infrastructure is inadequate to meet rising consumer needs and expectations. A sharp decline in critical infrastructure investment over the last decade has already left portions of the power delivery system vulnerable to poor power quality, service interruptions, and market dislocations. Substantial system upgrades are thus needed just to bring service back to the level of reliability and quality already required and expected by consumers, and to allow markets to function efficiently so that consumers can realize the promised benefits of industry restructuring.

CEIDS can play a vital role in enabling the necessary upgrades and laying the foundation for the infrastructure needed in the future. The CEIDS vision is "to develop the science and technology that will ensure an adequate supply of high quality, reliable electricity to meet the energy needs of the digital society." To achieve this vision, the mission of CEIDS is to provide the science and technology that will power a digital economy, as well as integrate energy users and markets through a collaboration of public, private, and governmental stakeholders.

Power electronics-based controllers are essential to the realizations of the CEIDS vision and mission because the technology provides unprecedented levels of power flow control and operating flexibility. As a result, power delivery system operators can more reliably deliver more electricity to meet the demands of consumers—and do so *using existing power delivery equipment.* The devices allow operators to essentially dial in the desired flow on a particular transmission line. Power electronics-based controllers of various sorts can also help address power distribution problems impacting power quality.

Existing Infrastructure Vulnerabilities

Although the North American power delivery system has been running relatively smoothly, it is not impervious to increasing stresses from a variety of sources, including bulk power transfers on the wholesale market, an electricity demand and transmission capability mismatch, and the rise of digital loads that require high quality power.

Bulk power transfers in a deregulated market. The high-voltage transmission lines that form the backbone of the North American power delivery system are becoming an increasingly hot property with the advent of competition in wholesale electricity markets. The desire to obtain the lowest-cost generation leads to an increase in the number of power transactions, all of which are carried over the transmission grid. Energy companies, their unregulated generating subsidiaries, and independent power producers are relying to an unprecedented degree on the power delivery system's interconnected transmission networks to transfer large amounts of bulk power over greater distances.

In addition to these increased demands on the power delivery system, "wheeling" bulk power through existing transmission systems inevitably leads to uncontracted and undesired parallel- and loop-flows of power. The reason for this is that part of the line current from the sending-end flows through each available parallel path in proportion to its admittance. These loop flows often overload some power delivery equipment and can cause thermal and voltage variation problems.

Electricity demand and transmission capability mismatch. Another stress is the imbalance between growth in demand for electric power and enhancement of the power delivery system to support this growth. From 1988 to 1998, total electricity demand in the U.S. rose by 30 percent, but the capacity of the nation's transmission network grew by only 15 percent. This disparity is anticipated to increase from 1999 to 2009: demand is expected to grow by 20 percent, while planned transmission is expected to grow by only 3.5 percent.

Yet despite the heavy demands on the power delivery system, virtually no new transmission circuits are being built. The limited construction is due largely to the inadequate and/or uncertain investment return from such lines and difficulty in obtaining new rights-of-way. No one wants new construction in their backyard—a problem that affects not only power delivery equipment, but also freeways, dams, and airports. The result is the existing transmission system is being called upon to perform functions on a scale for which it was not originally designed.

Digital loads and poor power quality. At the same time, the *nature* of electricity demand is undergoing a profound shift in industrialized nations around the world. Twenty years ago, when the personal computer was introduced, few foresaw the widespread proliferation of "smart" devices. Today, for every microprocessor inside a computer, there are 30 more in stand-alone applications, resulting in the digitization of society. In applications ranging from industrial sensors to home appliances, microprocessors now number more than 12 billion in the U.S. alone.

These digital devices are highly sensitive to even the slightest disruption in power (an outage of less than a fraction of a single cycle can cause the device to malfunction), as well as to variations in power quality due to transients, harmonics, and voltage surges and sags. "Digital quality power," with sufficient reliability and quality to serve these growing digital loads, now represents almost 10 percent of total electrical load in the U.S., and this number is expected to increase significantly. The current electricity infrastructure in the U.S., designed decades ago to serve analog (continuously varying) electric loads, is unable to consistently provide the level of digital power required by our digital manufacturing assembly lines, information systems, and even our home appliances.

How Power Electronics Helps Address These Vulnerabilities

To address these vulnerabilities, power electronic-based transmission controllers represent a technological alternative to the brute force, traditional solution (i.e., massive reinforcement of the power delivery system). In most cases, the traditional option is no longer economically or politically viable. Power electronics-based controllers can help the power delivery system withstand stresses by increasing the effective capacity of existing power delivery equipment; and increasing power delivery system stability, reliability, and power quality for bulk transfers and digital loads.

Maximize Transmission Capabilities of Existing Infrastructure. Although power electronics-based T&D controllers will never be able to completely eliminate the need for construction of new transmission lines, their application can significantly increase present utilization of the existing delivery infrastructure. Traditional, electromechanical controllers have very limited capabilities and are too slow to govern the flow of alternating current in real time, resulting in loop flows and bottlenecks. Converter-based controllers, on the other hand, have the potential to act quickly enough to provide such control, enabling increases in power transfer capability by 30 to 60 percent, depending on the specifics of the transmission system. These increases in transmission capability will allow existing lines to meet rising electricity demand for many years. In economic terms, this boost in power delivery capability translates into less construction, reduced capital expenditures, rapid payback of capital, and in many cases, an alternative to the growing difficulty of siting new lines.

This boost in power transfer capability is possible because the power electronics devices (converter-based controllers, in particular) have the unique ability to control both real and reactive power, which enables operators to achieve maximum utilization of power delivery assets. Operators can use these devices to simultaneously, instantaneously, and independently control all three parameters—impedance, voltage, and phase angle—that determine the direction and magnitude of both real and reactive power flow on a transmission line. In other words, they provide power delivery system operators much more control over the flow of electricity. Dynamic control of these parameters transforms the transmission lines from passive elements into active elements that can be independently adapted to share predetermined real and reactive power flow levels, without adverse impact on transmission voltage quality.

Power Electronics-Based Controllers Save Utilities Money

Application of a Unified Power Flow Controller (UPFC) at American Electric Power's (AEP) Inez substation increased the power transfer capacity over the 138-kV Big Sandy-Inez line by at least 100 MW. This increase allowed AEP to defer construction of a new 345-kV line by at least three years, at an approximate cost savings of $8 million. By reducing real power losses on AEP facilities by more than 24 MW, the UPFC and other associated improvements provided further cost benefits of about $5 million annually or $22 million over the life of the project.
Source: EPRI Innovators, IN-113526

Power-electronics based controllers provide such control because they use high power, high voltage, solid-state switches to synthesize controlled current and voltage components that are injected into the transmission system. The controlled, injected current and voltage components enable fine control over transmission voltage and apparent transmission impedance—and the real and reactive power flows on transmission lines. This provides full control of point-to-point real and reactive power flow, with no loop flows or parallel flows. Furthermore, these controlled, injected current and voltage components can relieve transmission bottlenecks without having to build bypass transmission lines.

Uncontrolled power flows through the path of least resistance, which can result in under-utilization of some transmission lines and over-utilization of other transmission lines (which can lead to power outages for customers). The example in Figure 1 shows a bottleneck on path 2-3 and underutilized transmission on several paths, including path 4-5.

This uncontrolled power delivery system is analogous to uncontrolled water flow. Power electronics-based controllers function like the control valves and variable speed pumps in a water distribution system of reservoirs, pipes, and faucets. Along with surge-absorbing storage tanks, these valves and pumps enable improved overall control of water flow patterns. Power systems—in which voltage and electric current correspond to water pressure and rate of flow—need the electrical equivalents of valves, pumps, and storage, which power electronics provides. As a result, system operators can finely control power flow through various transmission lines, prevent under- and over-utilization of lines, and safely enable maximum utilization. In Figure 1, such control would enable elimination of the bottleneck on path 2-3 by directing the flow to other paths.

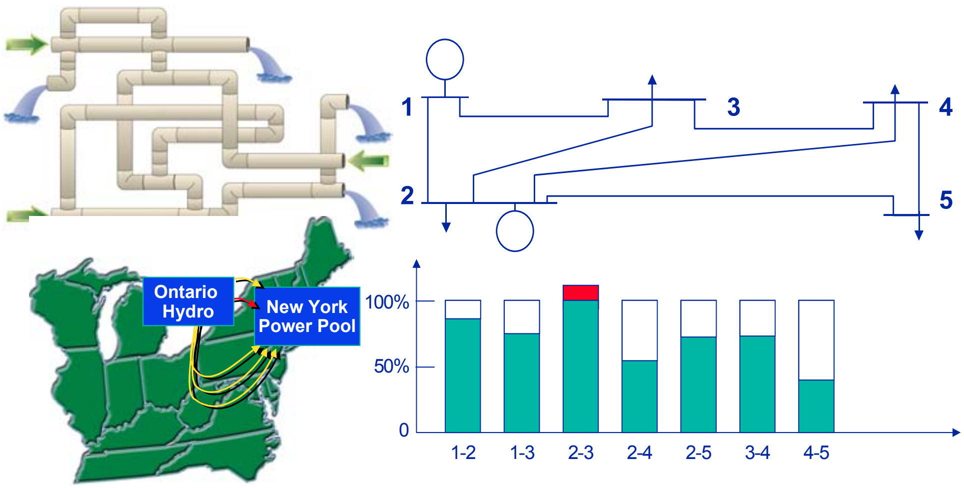

Figure 1. The Risks of Uncontrolled Power Flows.

Increase System Stability, Reliability, and Power Quality for Bulk Transfers and Digital Loads. Power electronics can enhance power delivery system reliability by counteracting transient disturbances almost instantaneously and providing wide-area voltage support. Furthermore, they are able to offer these capabilities while preserving the stability and reliability of high-voltage power delivery equipment that was not designed to serve as an integrated, interstate highway system for electricity.

On distribution systems, converter-based technology has been instrumental in solving power quality problems such as voltage sags, voltage flicker, and harmonics at a number of installations. Multiple power electronics-based controllers, connected in series and coupled with related hardware and digital control systems, can switch megawatt levels of power within milliseconds to synthesize a smooth, sinusoidal voltage waveform—the electrical components of which are independently variable. As a result, consumers benefit from higher quality power.

Converter-Based Power Electronics Controllers Are a Necessary Component of the Power Delivery Infrastructure of the Future

Currently, two types of power electronics-based power flow controllers are commercially available: 1) conventional, thyristor-based controllers and 2) converter-based controllers. For well into the foreseeable future, *converter-based* controllers will be the critical technology lynchpins of an advanced power delivery infrastructure, as envisioned by CEIDS. These controllers allow much higher utilization of existing T&D capacity (compared to thyristor-based controllers), while maintaining adequate system stability margins. They also represent the most viable and promising, near-term solution for maximizing the use of existing power delivery networks.

Conventional, Thyristor-Based Technology

Thyristor-based power electronics is a fairly mature technology with about 800 installations worldwide. This technology is capable of solving the basic needs of voltage support and power flow control in a relatively straightforward manner. Power circuits and control algorithms are substantially the same for all manufacturers. These devices can provide the basic functions of voltage and flow control, and their reliability now generally meets utility requirements.

However, thyristor-based controllers can only be used in a limited number of applications because their circuit concept and structure restrict their functional capability to those of a reactive shunt or series compensator. In addition, despite their value in some cases, thyristor-based controller solutions are cost prohibitive for many areas of the country. Further R&D investment in this technology is not likely to yield appreciable future cost improvements or new application benefits for two reasons. First, both the semiconductor device and circuit technologies are mature. The second reason is that the cost of the electronic content is a relatively small fraction (20 percent) of the total installation cost, which is dominated by the cost of conventional components and labor. Given the breadth of T&D challenges, this technology holds limited promise when compared to emerging, converter-based power flow controllers.

Emerging, Converter-Based Technology

The emerging, voltage-sourced converters (VSCs) include the following devices:

- STATic synchronous COMpensator (STATCOM)
- Static Synchronous Series Compensator (SSSC)
- Unified Power Flow Controller (UPFC)
- Interline Power Flow Controller (IPFC)
- Back-to-Back Tie (BtB)

The T&D applications for converter-based technology are numerous, in part because the circuit approach is still an open area for R&D. The resulting versatility and functional capability of these controllers enables them to provide solutions to essentially any transmission problem related to the control of power delivery system variables, as well as provide rigorous transmission flow management for power delivery system optimization.

Converter-Based Power Electronics Controllers Deliver Results

Tennessee Valley Authority (TVA) saved $14 million by joining with EPRI to install a pre-production Static Synchronous Compensator (STATCOM) instead of a second transformer bank at its Sullivan substation. In addition, STATCOM implementation is expected to reduce TVA's use of load tap changers, saving $1 million per avoided transformer failure.
Source: EPRI Innovators, IN-107577

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These synergistic transmission controllers can handle practically all voltage support, power flow and stability problems. Moreover, due to their unique ability to independently control, in real time, the transmission parameters of line voltage, impedance and angle, and thus to change almost instantaneously the flow of real and/or reactive power on a line, they enable maximum utilization of existing power delivery equipment. The capability can also be used to control line loading, minimize parallel and loop power flows, tie together asynchronous systems, and connect remote power generation (e.g., windmill farms) to the power delivery system.

Converter-based technology also solves many distribution problems regarding power quality as well. The capabilities of the distribution static compensator (DSTATCOM) and the dynamic voltage restorer (DVR), together with active filters for solving power quality problems such as voltage sags, voltage flicker and harmonics, have been successfully demonstrated at a growing number of installations.

Distribution System Benefits of VSC Devices

Employing a DSTATCOM to mitigate sawmill-generated voltage flicker "polluting" a 25-kV distribution feeder enabled BC Hydro to avoid implementation of any of the traditional solutions and save $400,000-$1.2 million on installation costs alone.
Source: EPRI Innovators, IN-110299

Installation of a DSTATCOM system on AEP's distribution circuit tamed severe voltage flicker on the line at a cost savings to the utility of more than $600,000, compared to the conventional solution of constructing a new distribution substation.
Source: EPRI Innovators, IN-111241

Widespread Adoption of C*onverter-Based* Controllers Will Provide Opportunities to Solve Diverse, Complex Problems

While thyristor-based controllers are commercially available and beneficial, widespread adoption of *converter-based* controllers will provide opportunities to solve a much wider range of problems because of their diverse application potential and greater functionality. Converter-based controllers offer the following unique features and functionalities:

- Uniformity and modularity (the same modularly constructed converter can be used for shunt and series applications, as well as voltage and power flow control)
- Convertibility (the transmission controller is functionally convertible, e.g., a shunt compensator can be converted into a series compensator or vice versa)
- Expandability (the transmission controller is functionally expandable, e.g., it can be expanded from a single-line controller to a coordinated multi-line controller system)
- Shunt and series compensation for voltage support and power flow control that can be maintained with depressed bus voltage (shunt) and a wide range of line current variation (series).
- Unique capability to simultaneously control transmission voltage, impedance, and angle; or alternatively, independently control active and reactive power flow.
- Unique capability to control and balance active and reactive power in a multi-line system.
- Unique capability to tie two or more systems, synchronous or asynchronous, and inherent terminal voltage support capability via controllable reactive (capacitive and inductive) compensation.
- Unique capability to couple energy storage to AC systems.
- Small physical size and potential for minimum installation labor (can be factory assembled).

These features and functionalities enable utilities and system operators to realize important benefits that can dramatically improve power flow and reliability, while reducing capital expenditure costs.

Defer or avoid transmission line construction. Converter-based controllers can enable operators to squeeze more power from the grid. In economic terms, the resulting 30 to 60 percent boost in power delivery capability translates into less construction, reduced capital expenditures, rapid payback of capital, and in many cases, an alternative to the growing difficulty of siting new lines. If power electronics controllers are extensively deployed throughout the North American power delivery system, system operators will essentially be able to dispatch transmission capacity across each interconnection as needed, facilitating open access.

Eliminate bottlenecks. Converter-based controllers relieve transmission "bottlenecks" without having to build "by-pass" transmission lines. Bottlenecks are caused by unintentional loop flows of electricity beyond a contractual path (due to uncontrolled power flows), and they result in limited power transfer capabilities. In the North America market alone, every major utility that operates a transmission grid has at least one bottleneck in the flow of power[1].

For example, many of New York's major transmission lines converge in central New York, resulting in a bottleneck in the flow of power from the western and northern regions to the eastern region. This bottleneck is a key strategic interface for the New York Power Authority (NYPA) and the New York independent system operator (NYISO), which operates New York's transmission system. Any interruptions or undesirable conditions at this bottleneck can potentially disrupt power to millions of homes. To ease this bottleneck, a converter-based controller was installed in 2001 at NYPA's Marcy substation as part of a project that will increase power flow transfer limits by 240 MW—approximately enough electricity for more than 200,000 homes. Operators can "mine" this power precisely when they need it most, during contingency situations. In addition to enhancing power transfer capabilities, the converter-based enhances voltage control, provides additional damping in response to system contingencies, and provides operational flexibility during system outages.[2]

Reduce the need for Transmission Line Relief (TLR). Converter-based controllers can also reduce the need for transmission line relief (TLR) activities. The frequency at which system operators must call for TLR indicates how often transmission levels are at or near capacity. TLR frequency is skyrocketing (see Figure 2). Solving the problem involves either building costly new transmission lines or investing in lower-cost converter-based controllers.

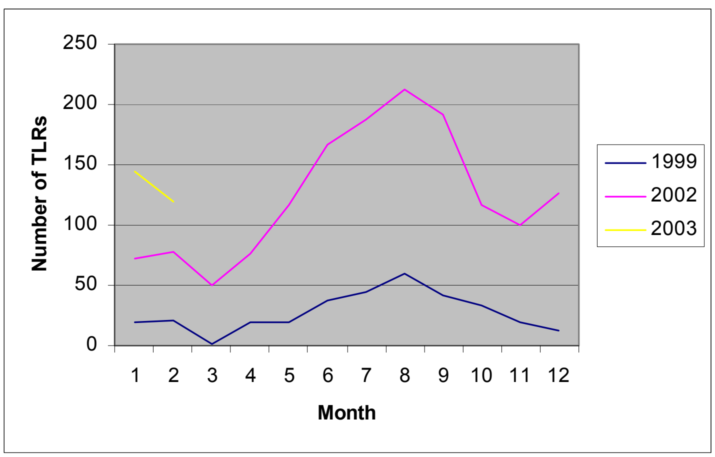

Figure 2: Rising Number of Calls for TLR
The rising number of calls for Transmission Line Relief (level 2 or higher) reflects the increasing inability of the transmission system to accommodate open markets. (Source: NERC web site logs)

[1] "Power Precision with UPFC," EPRI Journal, November/December 1998.
[2] "Squeezing More Power from the Grid," A. Edris, S. Zelingher, L. Gyugyi, L. Kovalsky. IEEE Power Engineering Review, June 2001.

Factors Currently Limiting Adoption of Converter-Based Controllers

To realize these and other benefits, converter-based technology must be widely adopted and implemented across North America. But additional R&D must be completed to enable such widespread adoption. This R&D must address several factors currently limiting widespread deployment of converter-based controllers: 1) the somewhat lower reliability/availability of these controllers (compared to thyristor-based controllers), and 2) the relatively higher cost of these controllers.

Reliability and Availability Problems. The present availability and reliability of converter-based controllers need to be improved to meet utility standards. Reliability problems appear to be related to the structure of the converter, the use of an indirect rather than direct interface, and the difficulties of implementing rigorous protection schemes using power semiconductors of relatively long turn-off time delay. The proposed R&D would address these structural problems and difficulties, thereby eliminating the reliability and availability barriers hindering widespread adoption.

Performance and Cost Issues. Fundamentally, a converter-based transmission controller has two major constituents: 1) the converter proper (including control, cooling, and support equipment) to generate the required output for compensation, and 2) the magnetic interface (coupling transformer and auxiliary magnetic components, if used) to connect it (in-shunt or in-series) to the AC system. These two main constituents primarily determine the performance, reliability and cost of an installation.

Regarding the first constituent—the converter proper—converter-based technology has a high electronic cost component and small installation size and labor requirements. Hence, advancements in the power semiconductor device and circuit could have major impacts on the equipment size, installation labor, and overall capital cost required.

In fact, new emerging power semiconductors exhibit significantly improved switching characteristics that facilitate different output voltage synthesis methods, more flexible converter control, and tighter protection. The emerging, new power semiconductors provide flexibility that was not available for the converter design of early transmission controllers. The flexibility provided by precisely controllable, fast switching with almost negligible delay makes it possible to increase converter utilization and significantly improve protection, and thereby increase reliability and reduce the cost of the converter proper.

The improved capabilities of power semiconductors also offer a possibility to consider the issue of magnetic interface presently used to couple the converter to the AC system. Currently, the series coupling transformers within converter-based controllers cause performance limitations due to their tendency to saturate during dynamic voltage excursions. At the same time, the cost of converter-based controllers remains too high for large-scale applications because they require costly specially-designed transformers. The latest STATCOM designs focused on the use of standard step-up transformers to couple the converter in shunt-connection to the AC system. None of these approaches seem to have the potential to provide all the structural and operating characteristics required to economically meet the broad application requirements of power delivery systems.

The simplification, or total elimination of the magnetic interface via suitable converter design and use of new semiconductors seems to be the only reasonable alternative to achieve the combination of cost, reliability, and performance needed.

R&D Needed to Advance Converter-Based Controllers

Additional R&D must be completed to facilitate widespread commercial adoption of converter-based controllers. To address this need, EPRI proposes a focused R&D project that addresses the most important issues of converter-based power flow controllers: simplified converter structure and elimination of the need for a series coupling transformer. The project involves development of a directly coupled (no series transformer), converter-based power flow controller.

To eliminate the transformer from the controller, EPRI proposes the development of an "H-bridge" converter structure for direct series connection in the transmission line for the low cost realization of the SSSC and the UPFC in transmission applications, and the DVR and DSTATCOM in distribution applications. The converter would employ the switching capabilities of emerging power semiconductors to produce the desired output voltage waveform without a complex magnetic circuit structure. Successful completion of the program is expected to result in a low cost, reliable and highly versatile converter structure for both transmission and distribution applications—exactly what is needed to ensure widespread adoption of this technology. In addition, it is expected that the proposed R&D will reduce costs by 20 percent, compared to existing converter-based controllers.

Value and Commercialization of Proposed R&D

This project would develop a new, simplified converter structure using new, evolving advanced semiconductors, which can be directly connected in series with the line without a coupling transformer. (The converter structure envisioned would, of course, be suitable for use with a coupling transformer of standard design, if the application, or user preference, requires it.) Apart from the eliminating the need for a series coupling transformer (which would significantly lower the cost of the units), the development would also aim for high reliability and the full MVA utilization of the converter (through simplified converter structure and rigorous protection algorithms afforded by the greatly improved characteristics of emerging semiconductors). These changes would enable converter-based controllers to meet cost, reliability, and availability requirements of utility applications.

The resulting directly-coupled power flow controller would not be constrained by magnetic design limitations, and as a result, would have the operating freedom and speed to handle practically any type of power flow, compensation, and power quality problem encountered on a transmission or distribution line. These capabilities would make it attractive not only for applications on long transmission lines, but also in meshed systems. In the latter case, compact solid-state controllers with relatively small MVA ratings could provide effective power flow control and loop-flow mitigation at relatively low cost.

The proposed converter is expected to use one of the emerging, advanced power semiconductors (i.e., Integrated Gate Commutated Thyristor (IGCT), Insulated Gate Bipolar Transistor (IGBT), and Super Gate Turn-Off (S-GTO)), but will also be able to leverage more advanced power semiconductors (such as silicon carbide devices) as they become available. Furthermore, the new converter design is expected to have modular parts, such as a switching pole, that can also be applied in a three-phase converter arrangement. This modularity will enable cost effective, modular structures for advanced converters in both single-phase and three-phase applications.

The CEIDS commercialization strategy is the same as EPRI's strategy: after completion of the R&D, E2I will license the results of the proposed R&D to an appropriate manufacturer. In this case, it is very likely that the company that performs the R&D will also be the commercializer.

Proposed Project Phases and Timeline

The directly coupled converter program is proposed in the following four phases:

- Phase 1: Evaluate and select power semiconductors; conceive, evaluate and select valve, pole and converter structure; review, devise, and evaluate output waveform synthesis techniques; establish and evaluate candidate circuit(s) by computer simulations and define final converter.
- Phase 2: Develop, fabricate, install and evaluate the power flow controller with appropriate controls in a suitable distribution application, operating it as an SSSC and/or a DVR.
- Phase 3: Add a second converter to the installation in back-to-back connection to facilitate the operation and evaluation of the UPFC.
- Phase 4: Design, fabricate, install and evaluate the directly coupled power flow controller in a suitable transmission application, operating it as an SSSC and a UPFC.

The development period of the directly coupled converter-based power flow controller is estimated at 4-5 years, depending on whether the actual installation would be operated only as an SSSC or also as a UPFC.

The Larger Effort to Advance Power Electronics-Based Controllers

Key existing or planned R&D initiatives to advance power electronics-based controllers that would complement the proposed CEIDS R&D include development of integrated control capabilities and development of post-silicon technology. These R&D initiatives, as well as others, are part of an ongoing effort to accelerate advancements and facilitate the widespread adoption of power electronics-based controllers (see Figure 3).

Development of Integrated Control Capabilities. At this time, power electronics-based devices are individually controlled. Achieving a higher available transfer capability (ATC) for a transmission system calls for consideration of power electronics control from a systems point of view. In other words, new system control logic is needed that allows the integrated control of multiple power electronics-based devices to provide maximal ATC while maintaining system dynamic security, including voltage security. EPRI has conducted early R&D to identify control coordination approaches and develop a common modeling framework of power electronics-based controllers for load flow and power dispatch.

Development of Post-Silicon Technology. Post-silicon technology, such as silicon carbide (SiC) and gallium nitride, is expected to offer the potential for dramatic improvements over what today's silicon devices can do. They will also reduce the cost of AC/DC converters, enabling interconnections between asynchronous power systems and long-distance, high-voltage DC transmission. What's more, once these devices are in mass production, they promise to reduce the costs of power electronics devices.

Major research efforts in this area are currently being funded through the Office of Naval Research, U.S. Department of Energy's Basic Energy Sciences program, the U.S. Defense Departments Advanced Research Projects Agency (ARPA) as well as substantial work in private laboratories. For example: ABB has invested over $100 million in developing SiC for applications in the electric power industry. General Electric has made a substantial investment in developing SiC GTO thyristors and devising power system applications in partnership with the U.S. Defense Departments Advanced Research Projects Agency (DARPA). Tennessee Valley Authority continues to sponsor work on chemical vapor deposition diamond technology. From 1997-2001, EPRI's Strategic Science & Technology (SS&T) program and the DARPA funded and completed six projects totaling $14 million to accelerate the development of high-power devices and circuits that can switch or control DC or AC power levels of 100 kW and above.

Following up on the joint research program, EPRI's SS&T program has launched three projects in 2002 that fill key gaps in the development of these materials specifically for the electric power industry.

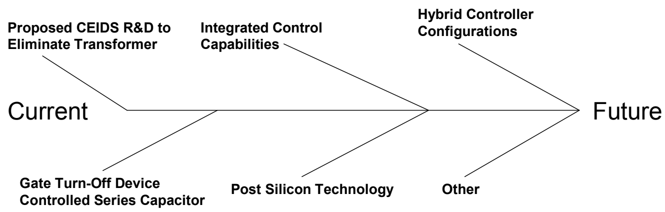

Figure 3. Complementary R&D Initiatives in Power Electronics-Based Controllers

Advanced power-electronics-based controllers are also a key component of a broad "smart power delivery system." The self-healing system is envisioned to be always-on and "alive," interconnected and interactive, and merged with communications in a complex network of real-time information and power exchange. It will be constantly self-monitoring and self-correcting to maintain the flow of secure, high quality, reliable power. It will sense disturbances and counteract them, or reconfigure the flow of power to cordon off a disturbance before it propagates. The system will also be smart enough to seamlessly integrate traditional central power generation with an array of locally installed, distributed energy resources into a regional network.

Will Others Conduct the Proposed R&D?

In general, CEIDS funds projects that benefit from a collaborative approach to R&D. Collaboration leverages diverse financial, technical, and human resources for the benefit of the participating stakeholders. In most cases, CEIDS projects would be prohibitively expensive for one stakeholder alone or even a small number of stakeholders to undertake. In the current economic climate, projects that require a multi-year R&D cycle are even less likely to be funded by an individual stakeholder or alliance between a few players, such as utilities and/or electronics companies.

The proposed power electronics-based R&D in CEIDS clearly falls into this project category because it is a multi-year project that will require significant collaborative R&D to accomplish. For this reason, it is highly unlikely that individual stakeholders or even a small alliance of stakeholders will undertake it. But working together with CEIDS, it is highly likely that both utilities and electronics companies will be willing and able to invest in a fraction of the total cost as part of a collaborative effort that will be highly beneficial for all participants.

Conclusion

Given the severity and breadth of current transmission and distribution challenges in the U.S., and the fact that power electronics-based controllers offer viable, low-cost solutions to these challenges, widespread adoption of power electronics-based controllers is necessary for the attainment of the CEIDS vision. In particular, *converter-based* controllers are a crucial component of the future power delivery infrastructure because they enable operators to maximize the use of existing power delivery equipment, avoid and/or defer the construction of new transmission lines, eliminate bottlenecks, and avoid TLRs, as well as finely control power flow for improved power reliability and power quality. This technology offers significant improvements in power transfer capabilities, voltage control, contingency planning, and operational flexibility, and offers almost unlimited potential to solve fundamental infrastructure problems.

To realize these benefits, additional R&D must be completed that will facilitate widespread adoption of converter-based controllers throughout North America. The proposed CEIDS R&D will address key barriers limiting widespread adoption of converter-based controllers—low reliability/availability, high cost, and lower-than-desired performance. This proposed R&D will also complement other power electronics R&D currently underway, resulting in significant, simultaneous advancements in this important technology.

Given EPRI's 30-year track record of effectively managing complex technological projects, collaborative R&D like this project plays to EPRI's strengths and those if its affiliate, E2I. Under the leadership of the CEIDS Initiative, stakeholders can contribute to the proposed power electronics-based controller R&D and realize the significant and lasting benefits of converter-based power electronics.

For More Information

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