Dynamic Sag Correctors:
Cost Effective Industrial Power Line Conditioning

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Abstract—Voltage sags, transients, and momentary interruption of power together constitute 92% of the PQ problems encountered by typical industrial customers. The series-parallel connected Dynamic Sag Corrector (DySC) provides statistically significant protection at greatly reduced cost. The DySC is rated 1.5 kVA 1-phase to 2000 kVA 3-phase and features a patented single stage power conversion circuit with minimal stored energy. A unique circuit allows operation with opened upstream circuit breaker. The paper presents a detailed discussion of DySC operating principles and validation of performance. It also provides conditions under which this new category of product can be applied.

I. Introduction

Productivity loss due to deep voltage sags and brief power interruptions has been called "the most important concern affecting most industrial and commercial customers," costing billions of dollars every year in the United States alone [1,2]. These power quality (PQ) events typically last for less than one second, impressing voltage sags down to 50% of nominal voltage, with occasional short-term interruptions lasting for approximately 6-to-10 cycles. However, when an industrial process is interrupted or shut down as a result of a power quality event, the process outage will be much longer than the duration of the PQ event itself. The costs of such PQ events—including long restart and cleanup times and scrapped product—have been computed in several studies and range from several hundred dollars for an easy restart to over $500,000 per event for semiconductor plants. Conventional solutions such as surge suppressors and voltage regulators do not solve the predominant problem and, while UPS systems can resolve the problem, their high acquisition and operational costs preclude applying them broadly for non-critical industrial and commercial processes.

As the industrial and commercial sector increases its dependence on sensitive electronic and power electronics process control equipment, its susceptibility to ubiquitous power quality problems is heightened. These well-recognized power quality problems include:

- voltage spikes and transients caused by lightning strikes on the utility system
- shallow and deep momentary voltage sags caused by faults on the utility system or at customer locations
- momentary interruptions caused by utility action to clear faults (up to 15 cycles)
- temporary or sustained interruptions resulting from faults located on a customer's distribution line (0.2 seconds to several hours)

Electrotek Concepts, in a study sponsored by the Electric Power Research Institute (EPRI), and in collaboration with 24 utilities, evaluated power quality disturbances over a period of 27 months from 1993 to 1995. Approximately 300 power quality monitors were installed in locations across the US, resulting in over 6 million power quality events being recorded. The cumulative data from the "Distribution Power Quality (DPQ) Study" indicates that 92% of all events correspond to voltage sags down to 40-50% of nominal line voltage, and that most of these events last for less than 2 seconds [2]. Longer-term interruptions (2 seconds to more than 10 minutes) proved to be rare, accounting for an additional 4% (for a total of 96%) of all power quality events. Similar data have been recorded in a survey of Canadian power systems [4]. For customers fed directly from high voltage transmission systems, interruptions were almost non-existent, and sags accounted for practically all of the power quality events recorded. Of even more importance than the mass of data itself, are follow-up studies, conducted by Electrotek, EPRI, utilities and industries, which confirm that processes and equipment subjected to these power quality incidents can face disruption and lost productivity. This enormous database provides an excellent snapshot of typical power quality problems faced by different types of utility customers and encourages the development of unique power quality solutions for potential customers.

Dynamic voltage regulators in various flavors have recently been developed by a number of companies, targeting voltage sag mitigation on the utility side of the meter, primarily for higher power applications rated at 2-10 megawatts at medium voltage levels. Most of these devices are still in the demonstration stage, and are being field tested with utility and Electric Power Research Institute (EPRI) support and subsidy. Similarly, the viability of a battery-less UPS type of device that provides from 2 to 5 seconds of protection has been explored by several manufacturers and utilities. These devices, which claim to offer more reliable protection than UPS systems, include superconducting magnetic energy storage systems (SMES), flywheel based systems, and static transfer switches (STS) for switching between independent utility feeds. Most of these devices are rated over 200 kVA, with ratings of more than 1.0 MVA being more common. Although cost continues to be a major issue (at $300-$1000 per kVA except for the STS), the operation and level of protection afforded by such devices has been amply proven in the field. While they provide adequate protection to the customer, the major question is who will pay for these (a 2 MVA unit is $0.5 to 1.0 million), and how can the payback period be justified.

More recently, a new category of product has become available, the Dynamic Sag Corrector (DySC, pronounced 'disk'). The DySC approaches the power line conditioning problem differently, recognizing that the operational paradigm for this category of product is of providing an "insurance" function. This suggests that the cost versus performance tradeoff has great relevance, and solutions that provide statistically significant protection at greatly reduced cost would provide substantial value to the end-use customers. The DySC targets voltage sags, transients, and momentary loss of power, which together constitute 92% of the problems encountered by the typical industrial customer. The DySC is rated at 1.5 kVA single phase to 300 kVA three phase in a transformerless implementation, and up to 2000 kVA in a uniquely configured series transformer connected device. The DySC is small (1/20th the size) and lower in cost compared to existing solutions because it 1) is transformerless, 2) features single stage power conversion, 3) optimally matches protection time to system characteristics, and 4) minimizes stored energy.

II. The Power Quality Problem

A. Causes of Voltage Sags

Transmission-level bulk power in the United States is extremely reliable, and complete outages are rare. Nevertheless, the physical nature of the distribution network makes voltage sags and momentary interruptions inevitable, notwithstanding the best efforts of individual utilities. Weather conditions, tree branch or animal contact, and insulation failures or human activity, can create single-line-to-ground (SLG) or line-to-line (L-L) fault paths, and rarely a 3-phase to ground fault. The relatively few customers near the fault will see a deep voltage sag, even to zero, followed by a complete interruption when the utility circuit breaker or fuse operates. But the vastly larger community of customers on other distribution feeders, and also those connected through the transmission system, will see a voltage sag—with a magnitude determined by the customer's distance to the fault location, and a duration often determined by the characteristics of the utility's circuit protection devices. These customers will be isolated by several transformer connections from the fault; it is these intervening transformer connections, as well as the related impedances, that decrease the depth of voltage sag seen by most customers [5].

Undervoltage conditions may also be caused by motor starting. These are usually 3-phase symmetrical sags of shallower depth and longer duration, which affect only the local area.

Statistical data have shown that most faults are SLG faults. The EPRI-funded DPQ study indicates that 92% of all PQ events correspond to voltage sags down to 40-50% of nominal line voltage, and that most of these events last for less than 2 seconds [2]. Longer-term interruptions are typically rare, accounting for an additional 4% of all power quality events. For customers fed directly from high voltage transmission systems, interruptions were almost non-existent, and voltage sags accounted for practically all of the power quality events recorded. The DPQ data for voltage sags are summarized in the chart in Fig. 1, which presents the number of voltage sags of a particular magnitude and duration expected at a typical site in one year. By far the greatest number of events are of short duration, less than one second, and leave 50% to 90% voltage remaining.

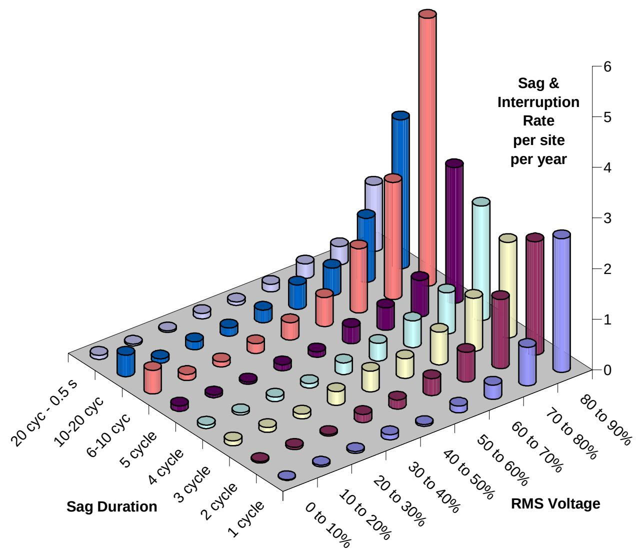

Fig. 1. EPRI DPQ study statistical site summary [2].

B. *Sensitivity of Industrial Equipment to Voltage Sags*

Switching power supplies, industrial control relays and contactors, solenoids, adjustable-speed motor drives, thyristor (SCR) controlled motor drives and rectifiers are all susceptible to short duration voltage sags. Although some equipment for some markets has been designed with internal energy storage to decrease voltage sag susceptibility, the cost pressures of the general market dictate that first cost be minimized. The typical end-use customer does not consider voltage sag sensitivity in his equipment buying decision.

The semiconductor industry, in standard SEMI F47 [7], and the Information Technology Industry Council (ITI, formerly CBEMA) [8] both recognize the susceptibility of equipment to voltage sags, and the related costs to the end-user, and have published recommended input voltage magnitude/duration curves that such equipment should tolerate. Even so, the DPQ data demonstrated a significant number of PQ events outside the CBEMA curve; this is shown graphically in Fig. 3.

The IEEE has recently developed a tool that helps industrial equipment users to evaluate the cost impact of voltage sags at their own plant: IEEE 1346-1998 [6]. The standard presents a method for combining statistically valid predictions of voltage sag magnitude, duration, and rate of occurrence, together with a characterization of plant equipment susceptibility to these PQ events, to determine the cost of sag-caused downtime. The cost of either power conditioning devices or new process equipment with greater voltage sag tolerance can also be compared against the downtime costs.

III. THE DYNAMIC SAG CORRECTOR (DYSC)

The Dynamic Sag Corrector was designed on the following principles

- Cost of ownership should be reduced by providing statistically significant insurance. The standard DySC protects against 92% of events categorized by the DPQ study by correcting voltage sags of 50% magnitude depth and up to 2 seconds duration.
- Size and weight should be minimized. The standard DySC products, up to 500 kVA modules, do not include a series transformer, and include little energy storage.
- Operating efficiency should be maximized. The DySC includes a static bypass switch that is normally closed until a sag event occurs, resulting in over 99% efficiency.

A. The single-phase MiniDySC

The single-phase DySC (MiniDySC) is derived from a patented voltage boost circuit [3,9], Fig. 2. The single-phase inverter is configurable to operate in voltage boost or bypass mode, and is capable of providing 100% boost to the incoming AC line voltage. This allows it to correct for deep voltage sags down to 50%. Further, the inverter DC bus provides the ability to also handle deeper voltage sags down to zero volts. The ride-through under these conditions is limited by the amount of stored energy. Typical U.S. utilities claim a breaker reclose time of 10-12 cycles, setting the target for stored energy that would provide a statistically meaningful level of ride-through protection.

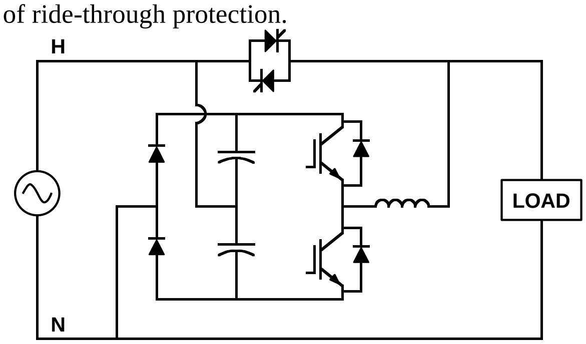

Fig. 2. The Single-Phase DySC Topology

Common to the entire DySC product line is the static-bypass switch, which remains on under normal power line conditions. This permits very efficient single-stage power throughput with no harmonic voltage content added.

When the input L-N voltage differs from the desired waveform, the static-bypass switch is turned off and the IGBT inverter begins operating. Thyristor commutation is hastened by the injected inverter voltage. The missing voltage on the input in calculated, and becomes the reference for the inverter voltage regulator. The inverter supplies only the missing voltage and the circuit is configured to add this missing voltage to the input voltage to provide the needed compensation. The time to detect the sag, commutate the thyristors, and begin compensation is less than 1/8 cycle.

Figure 3 shows sag events data recorded at a typical industry plant over a period of over 2.3 years [2], together with the old CBEMA curve and the newer ITI curve [8]. Overlaid on that is the protective regime of the standard DySC product, clearly indicating its efficacy in protection.

Rather than depending on stored energy to compensate the missing voltage, the DySC draws power from the input line whenever the missing voltage magnitude is 50% or less. The smaller DySC units include sufficient energy storage to compensate for 100% missing voltage for three cycles. Optional additional storage, in the form of capacitors, can increase the ride-through time to 15 cycles or more. This latter feature will allow the MiniDySC to protect against the interruption of power up to the first utility reclose operation following a fault, a prevalent type of PQ event in high-lightning suburban areas.

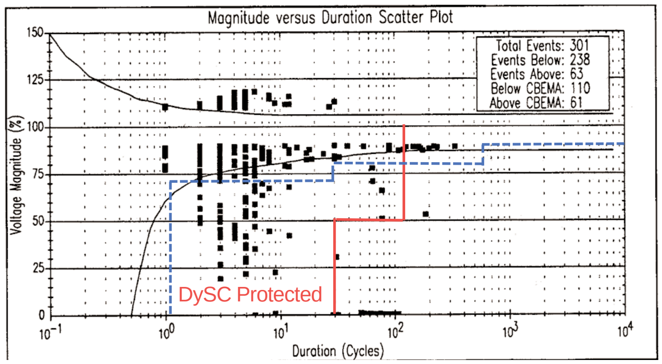

Fig. 3. Scatter plot of PQ events at one industrial site over 2.3 years, overlaid with: the CBEMA curve (solid thin lines), the ITI curve (dashed lines), the single-phase DySC protection regime (thick lines).

B. The Three-phase ProDySC and MegaDySC

For lower power three-phase 4-wire applications up to 500 kVA, the single phase DySC is adapted to realize a three-phase protection function in the ProDySC product. For higher power levels up to 2 MVA, a series transformer coupled device provides a more favorable solution, resembling other solutions in the market, such as GE's SSVR, SST's IVR, Westinghouse's DVR, and Siemens' Sipcon-S. These units operate by inserting a transformer in series with the line, and inject a voltage (using an inverter) to compensate for voltage sags. Most systems are limited to correction of voltage sags down to 50%. The DySC on the other hand can handle deep voltage sags, and can provide ride-through if adequate energy storage is provided.

One limitation of existing series-connected DVR type of solutions is the requirement for a 'low-impedance' current path on the utility side to allow the load current path to be completed, as seen in Fig. 4. Particularly at higher power levels, it is not clear that the balance of load on the 'cleared' side of the circuit breaker will provide a current path to sustain operation of the load. The higher power DySC units (MegaDySC), on the other hand, can operate either under a deep voltage sag situation or with an open upstream breaker. This unique capability (protected by pending patents) is shown schematically in Fig. 5.

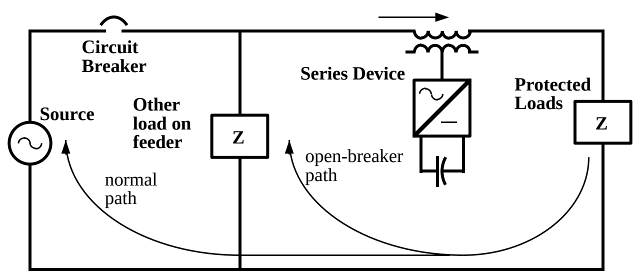

Fig. 4. Current path for series DVR-type device with open input breaker

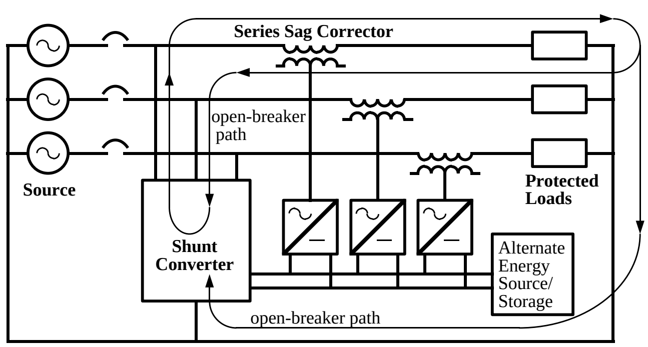

Fig. 5. The MegaDySC series-shunt circuit provides a load current circulation path (static bypass switches are not shown for clarity)

C. MegaDySC Combinations

For applications requiring ultra-reliable utility power, the only solution has been the use of multiply redundant sources including UPS, generators, and multiple distribution feeds. This is ironic when one considers that the utility transmission grid has extremely high availability, with only the occasional voltage sag to mar its near perfect record. However, at the distribution level, the availability is much lower, as local faults can cause a localized downstream outage to occur. The use of independent distribution feeds with static transfer switches or high-speed vacuum transfer switches has not been sufficient to solve the problem of sags and transfer interruptions. Consequently, this solution, with its higher cost to the utility, and its poor performance, has not been widely adopted. We are proposing an innovative technique to combine a fast vacuum transfer switch with a dynamic sag corrector to provide extremely reliable and available power, as seen in Fig. 6.

The recently introduced 27 kV vacuum transfer switches operate with an interruption time of 1.5 cycles. The MegaDySC, with its internal load current circulation path, is able to maintain load voltage through the transfer interval. Note that a strictly series connected device, such as the DVR, cannot provide this function. The DySC will also compensate for transmission-level voltage sags, which would appear on both the independent feeders.

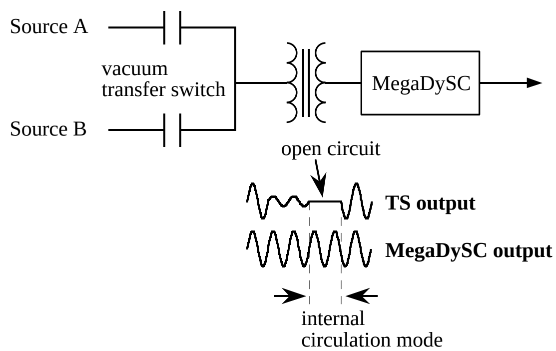

Fig. 6. Ultra-reliable power is supplied cost-effectively by using a vacuum transfer switch plus a voltage sag corrector with ride-through capability.

Other applications include a continuous duty rated DySC that operates as a utility interface for longer-term energy storage devices or alternative energy sources, but with the advantage that the energy source does not require fast transient response.

IV. TEST RESULTS

More than ten 300 kVA load rated three-phase DySC (ProDySC) units have been installed in the field. A voltage sag event recorded in July 2000 is shown in Fig. 7 for one 300 kVA unit that was fitted with input and output monitoring equipment. In this case the DySC used internal energy storage to provide 16 cycles of ride-through during what was, possibly, a utility breaker reclose operation.

Figure 8 shows production testing waveforms for a 300 kVA three-phase three-wire ProDySC correcting a symmetrical three-phase sag to 50%, while loaded to 80% capacity. The top waveform is one input line-line voltage. The bottom three waveforms are the DySC output voltages. It can be seen that the voltage sag is detected and corrected in approximately 2 ms.

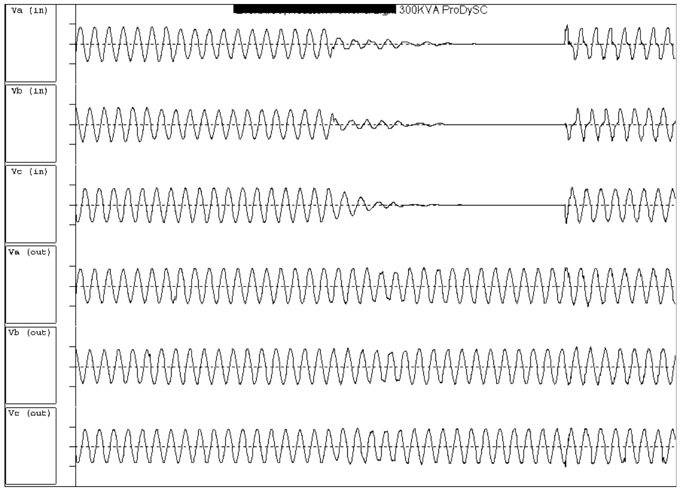

Fig. 7. 300 kVA ProDySC field monitoring data: Input (top 3 waveforms) and DySC output L-N voltages.

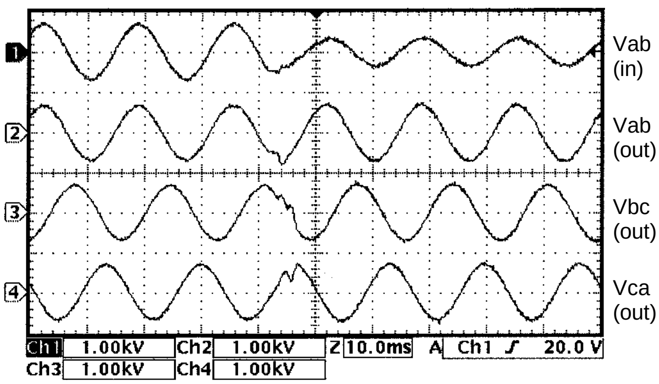

Fig. 8. 300 kVA ProDySC test plot: One L-L Input voltage (AB, top) and DySC output voltages (AB, BC, CA)

V. Conclusion

DySC products have been in limited production since October 1998. There is now a large installed base in critical process industries, including semiconductors, automotive, optical fibers, plastics, and CNC machining. DySC units have been shown to be smaller in size and lower cost, while providing a high level of protection. Correction for sags down to 50% as well as protection from momentary loss of power has been demonstrated. Operating efficiency is greater than 99%, response time is less than 1/8 cycle, and it is anticipated that it will have a long operating life of at least 10 years. The absence of batteries also minimizes operational and maintenance cost, and guarantees system availability.

The DySC can be integrated into industrial equipment to help equipment manufacturers meet the recommended input voltage magnitude/duration curve of standard SEMI F47 [7] or the ITI [8].

Table 1 compares the protection provided by the DySC as against other power line conditioning devices. In addition, the unique series-shunt connected MegaDySC product, coupled with a fast vacuum transfer switch, can provide extremely high power quality at a fraction of the cost of static transfer switches alone.

Table 1: Protection Capability for Various Power Conditioning Equipment

Type of Event	% of Total PQ Events	Spike Suppressor	Voltage Regulator	Transformerless DySC	UPS Systems
Spikes & surges	5%	Solves	Solves	Solves	Solves
Sag to 80%	35%	No	Solves	Solves	Solves
Sag from 50-80%	45%	No	No	Solves	Solves
Interruption 0-0.15 sec	7%	No	No	Solves	Solves
Interruption 0.15-500 sec	4%	No	No	No	Solves
>500 sec Outage	4%	No	No	No	No
Total PQ Events Solved	100%	5%	40%	92%	96%
kVA Range		1-1000 kVA	1-200 kVA	1-2000 kVA	0.2-1000 kVA
kVA / lb.		1-10	0.02-0.03	0.2-1.0	0.01-0.02
kVA / ft^3		500	1-2	10-50	0.3-1

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William E. Brumsickle received the B.S. degree in physics from the University of Washington (Seattle) in 1982, and the M.S. and Ph.D. degrees in electrical engineering from the University of Wisconsin-Madison in 1995 and 1998. He joined Soft Switching Technologies, where he is currently Technical Manager, in 1998.

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Robert S. Schneider has a B.S. degree in Physics/Mathematics from the University of Wisconsin-Eau Claire and an M.S. degree in electrical engineering from the University of Wisconsin-Madison, and is Engineering Manager - Standard Products at Soft Switching Technologies. He has over ten years of industrial experience in power electronic converter design and engineered system design and implementation of photo-voltaic, battery storage, motor drive, servo motor, and hydro-electric power conversion systems. He has also taught technical design training seminars. Some of the product design projects he has led at Soft Switching Technologies include: transformerless DySC products, high power automatic voltage regulators based on the RDCL inverter, and single-to-three phase power converter. Most recently, he has implemented demand flow technology techniques in forming product-manufacturing teams at Soft Switching Technologies.

Glen A. Luckjiff received the B.S. degree in electrical engineering from Lafayette College, Easton, PA, in 1989, and the M.S. degree in electrical engineering from Rensselaer Polytechnic Institute, Troy, NY, in 1991. After working for two years at GE Corp. R&D, he became a Ph.D. candidate in electrical engineering at the University of Wisconsin – Madison.

Since 1995, he has been a member of the technical staff at Soft Switching Technologies, Middleton, WI. His research interests are the theory and design of oversampled analog-to-digital converters, and control of power electronic systems.

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Mark F. McGranaghan directs projects and product development efforts related to power quality and power engineering at Electrotek. He is currently very active in a new alliance with E Source called the PQ Group and directs Electrotek Systems, a group at Electrotek that provides complete monitoring system solutions for electric utilities.

Mark has worked in the power quality area for 20 years, performing studies, teaching seminars, and developing products related to the analysis of power quality concerns. He worked closely with EPRI to help develop their power quality program, performed power quality case studies throughout the world, helped benchmark power quality in the US, and has helped over 25 utilities implement extensive power quality monitoring systems.

Mark works on numerous standards related to power quality. He has been Chairman of IEEE 519A, developing an application guide for applying harmonic limits. He has also worked on a number of IEC standards. He is currently active in defining indices for characterizing the reliability and power quality performance of power systems, increasingly important with deregulation of the industry.

Mark has BSEE and MSEE degrees from the University of Toledo and an MBA degree from the University of Pittsburgh.