Overcoming Cost Reduction Barriers for Advanced Power Quality Mitigation Systems

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Overcoming Cost Reduction Barriers for Advanced Power Quality Mitigation Systems

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REPORT SUMMARY

Background

There is a growing need to ensure electric service compatibility between end-user equipment and the utility power system. When does a perceived or real compatibility power quality problem exist? The simple answer is when any deviation of electricity applied to the equipment results in damage or misoperation of electronic systems or other electrical devices. A review of recent work targeted to quantify the financial losses and risks of power quality problems indicates different estimates from a few billion dollars per year to over $34 billion per year. The significant difference in reported financial losses indicates how the actual costs of power quality problems are so elusive. What is clear is that the total impact to the national economy is enormous and growing, and perhaps, more importantly, unknown.

New energy-storage technologies and new power electronics conversion configurations are providing new alternatives for power quality mitigation that may be increasingly attractive from an economic perspective. As these new and emerging power quality mitigation technologies are being developed and demonstrated in limited field operations, it is prudent to gain a better understanding of how to overcome equipment cost reduction barriers that exist in the marketplace.

Objectives

The purpose of this report is to provide insights to the number of market barriers for growing a successful power quality mitigation equipment industry based on mature, cost-effective products. This report describes basic issues of product development for power quality mitigation technologies as well as market reluctance due to customer issues, including cost. The driving forces behind cost reduction are highlighted along with a summary of the current and projected costs for a number of power quality mitigation system technologies.

Approach

The project team identified the most significant market barriers to overcoming product cost reductions by initiating discussions with equipment manufacturers and industry users, utility customer service personnel, and researchers involved in field demonstrations of various power quality mitigation systems. In addition, in-depth

reviews of power quality information from numerous referenced sources provided the basis for estimating the current prices and projected prices for equipment.

Results

Power quality mitigation systems are available today in numerous types and sizes and with varying functionality. A fair number of units have been demonstrated in the field; some are fully commercial products, and others are in prototype stages. Costs vary widely, but are trending downward. Cost reduction, while it is helped by technology advances, improved design, and constructive business attitudes, the single most significant product maturation barrier to cost reduction for most of the technologies studied was the lack of clearly defined technical specifications. Equipment specifications are essential to purchasing the "proper" power quality mitigation product. The procurement specifications must emphasize those requirements of particular interest for the intended applications. Volume production will come with standardization, but requires large market potential. Driving the market, in turn, requires education and an emphasis on raising the visibility of successful power quality equipment applications. Developers, users, and sponsors must all work together to bring power quality mitigation system technology to full utilization.

EPRI Perspective

By providing utilities with definitive insights to product maturation barriers to cost reduction for emerging power quality mitigation systems, EPRI is enabling utilities to better service key customer segments. Electric utilities are in a unique position to help industries understand and implement these new power quality mitigation systems. By surfacing and discussing the perceptions and the realities relevant to new power quality mitigation technologies, EPRI both assists and benefits utilities, their customers, and equipment manufacturers to obtain specified levels of power quality from standard electric service distribution systems.

Interest Categories

Power Conditioning
Commercial Customers
Power Quality
Energy Storage

Keywords

Power Quality
End-Use Mitigation Systems
Power Conditioning
Energy Storage

ABSTRACT

Electric power quality problems associated with interactions between distribution and end-user systems can be prevented. Established, new and emerging power quality mitigation technologies are either being applied, developed or being demonstrated in limited field operations to increase application understanding and build confidence in products. Since most business decisions are made on a sound economic basis, a required feature of power quality mitigation technologies is cost-effectiveness. However, there are a number of barriers to growing a successful power quality industry based on mature, cost-effective products.

In this report, both product and market readiness are discussed as barriers to cost reduction. The main focus of this study addresses basic issues of product development for power quality mitigation technologies as well as market reluctance due to customer issues, including cost. The driving forces behind cost reduction are highlighted along with a summary of the current and projected costs for a number of power quality technologies.

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INTRODUCTION

1.1 Background

Electric power quality problems associated with interactions between distribution and end-user systems can be prevented. While power quality is a well used (almost over-used) term, surveys of large users that buy power at transmission and distribution voltages turn up relatively few complaints about the quality of their incoming power, while surveys of small users connected at secondary voltages turn up numerous complaints about the quality of their incoming power. Three major changes in the characteristics of customer loads and power distribution systems have altered the nature of the power quality equation: (1) greater sensitivity of devices and equipment to power quality variations, (2) the interconnection of sensitive loads in extensive networks and automated processes, and (3) an increase in loads that use power electronics in some type of power conversion process.

These above-stated changes have created a growing market for “externally” power conditioned and “internally” hardened equipment that can protect loads from the wide variety of power quality variations that may cause productivity problems. Power quality problems can be complicated, involving the facility wiring, natural phenomena such as lightning, interacting facility equipment, and equipment connections to the electric power system. Most commercial and industrial production machinery are typically designed to operate with flawless electricity from the electric utility; however, many things interfere with electricity as it travels from the utility to customer’s equipment that produces revenue creating products and / or services.

1.2 Goals of this Study / The Problem of Cost Reduction

Established, new and emerging power quality mitigation technologies are either being applied, developed or being demonstrated in limited field operations to increase application understanding and build confidence in products. New energy storage technologies and new power electronics conversion topologies are providing new alternatives for power quality problem mitigation that may be increasingly attractive from an economic perspective. Since most business decisions are made on a sound economic basis, a required feature of power quality mitigation technologies is cost-effectiveness. However, there are a number of barriers to growing a successful power quality industry based on mature, cost-effective products. In this report, both product and market readiness are discussed as barriers to cost reduction. The main focus of this study addresses basic issues of product development for power quality mitigation technologies as well as market reluctance due to customer issues, including cost. The driving forces behind cost reduction are highlighted along with a summary of the current and projected costs for a number of power quality technologies.

1.3 Power Quality Applications and Requirements

Nowadays, tiny electric supply disturbances can generate big headaches. Electric service transient phenomena, often less than a few milliseconds, are nothing new, but they rarely phased older equipment. Today, delicate computer chips with microscopic wiring are less tolerant to electricity supply power quality problems. The results can be burned-out equipment, scrambled data, and lost revenue. The most significant power quality disturbances, in terms of disruption and financial loss to customers, are voltage sags and momentary interruptions. In general, customers understand that interruptions cannot be completely prevented on the power system. However, they are often less tolerant when their equipment misoperates due to momentary disturbances that can be much more frequent than complete outages. These conditions are characterized by short duration changes in the rms voltage magnitude supplied to the customer. The impact on the customer depends on the voltage magnitude during the disturbance, the duration of the disturbance, and the sensitivity of the end-use equipment.

Voltage sags and momentary interruptions are typically the most costly power quality variations affecting industrial and commercial customers. Faults over a wide area of the power system (transmission and distribution network) can affect the operation of a facility that has sensitive end-use equipment. Voltage sags and interruptions are inevitable on the power system, and are generally caused by faults on the utility system. Since it is impossible to completely eliminate the occurrence of faults, there will always be voltage variations to contend with. Storms are the most frequent causes of faults in most areas of the country. EPRI monitoring results clearly indicate that most disturbance events last only several seconds, as indicated in Figure 1-1. This comprehensive monitoring project was quite revealing and confirmed that the typical site incidence rate of sags and interruptions per month was over four (4) events lasting up to 0.2 seconds (approximately 12 cycles) that sagged the electric supply voltage by as much as twenty percent. To determine if an event of this nature would cause a problem, it is important to understand both the characteristics of the disturbance event and the susceptibility of the electronic system hardware to the disturbance event.

Consequently, it is often difficult to distinguish which characteristics of a given event are likely to cause electronic equipment to misoperate. Laboratory research and testing have provided constructive insights to the behavior of equipment sensitive to only the voltage during an rms variation i.e. undervoltage relays, process controls, motor drive controls, and many types of automated machines. Equipment sensitive to both the magnitude and duration of an rms variation includes virtually all devices that use electronic power supplies. Such equipment misoperates or fails when the power supply output voltage drops below specified values due to an ac input voltage event. These learning experiences were the basis for concentrating this study on those technologies that mitigate against short duration electric supply outages and voltage sags.

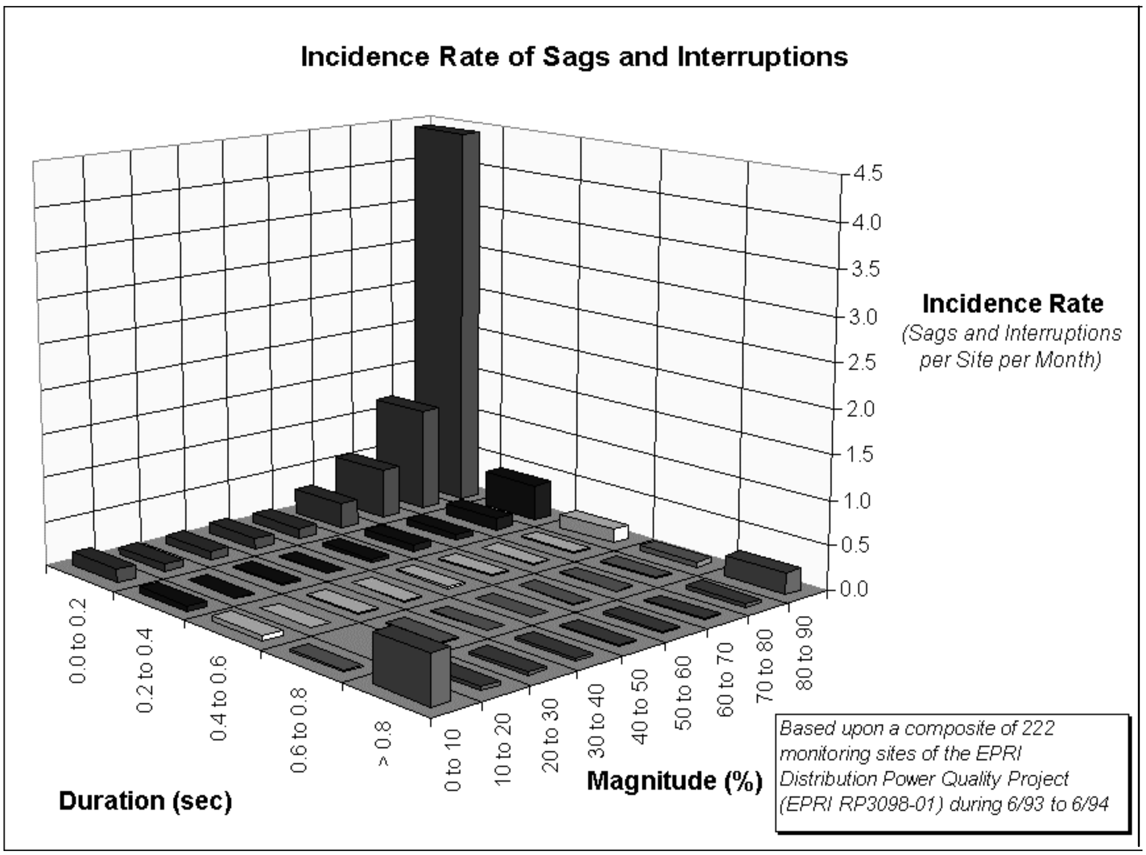

Figure 1-1
Results of EPRI Distribution Power Quality Study [1]

In the past, the conventional approach to mitigate against short duration outages and voltage sags has been to install battery-based uninterruptible power supplies (UPS) because this was the only technology readily available. However, conventional batteries are not well suited to pulse-like applications because only a small fraction of their energy can be drawn out in a short time. Generally, batteries offer optimum performance in terms of energy density when discharged over hours not seconds. Discharging batteries at fast rates reduces the energy available during the given discharge period. However, since the stored energy in the battery system is available for delivery in about one millisecond, with the proper use of power electronics, a high power density battery to cover voltage sags and momentary interruptions is a very real possibility. The power quality mitigation technologies reviewed here have been developed as a replacement for the conventional battery-based UPS. But, since they are new to the market, costs are presently higher than desired.

For the most crucial types of power quality problems, a modern solution is to supply power to ride-through an outage or support voltage through a sag for only a short period of time, often less than 1 second and usually not more than 15 seconds. The power quality mitigation technologies identified here are typically designed to operate from a minimum of about 1-second to a maximum of about 30 seconds, and to support all or part of the nominal load voltage. Naturally, power quality problems and solutions can vary dramatically depending on the nature of the problem, the existing electric service system, and the type, ratings and electromechanical performance characteristics of the specific commercial/industrial customer equipment.

For practical and economic reasons, the power quality problem must be defined in the context of the characteristics of the distribution system and load sensitivity. A farm in Iowa, a village in South America, the financial district of San Francisco, or a steel plant in Pittsburgh, require different PQ specifications. One technique developed by the Computer Business Equipment Manufacturer's Association (CBEMA) was to establish typical computer susceptibility limits within which computers would not generally be "upset or damaged." Figure 1-2 presents a CBEMA envelope (now called the Information Technology Industry Council – ITIC curve). This figure shows the applicable curve whereby electric service voltages (vertical axis) can have "variable amplitudes" for varying time durations (horizontal axis). This concept suggests that for electric service movement within the ITIC's envelope most single-phase 120Vac equipment would function normally. Conversely, should the electric service voltage fall outside the ITIC envelope, the voltage aberration would be a threat to the equipment's capability to perform within its technical specifications. For complete outage protection, as provided by a conventional UPS system, power may be transferred to a longer-duration power source such as a diesel engine, battery bank, or conventional fuel cell.

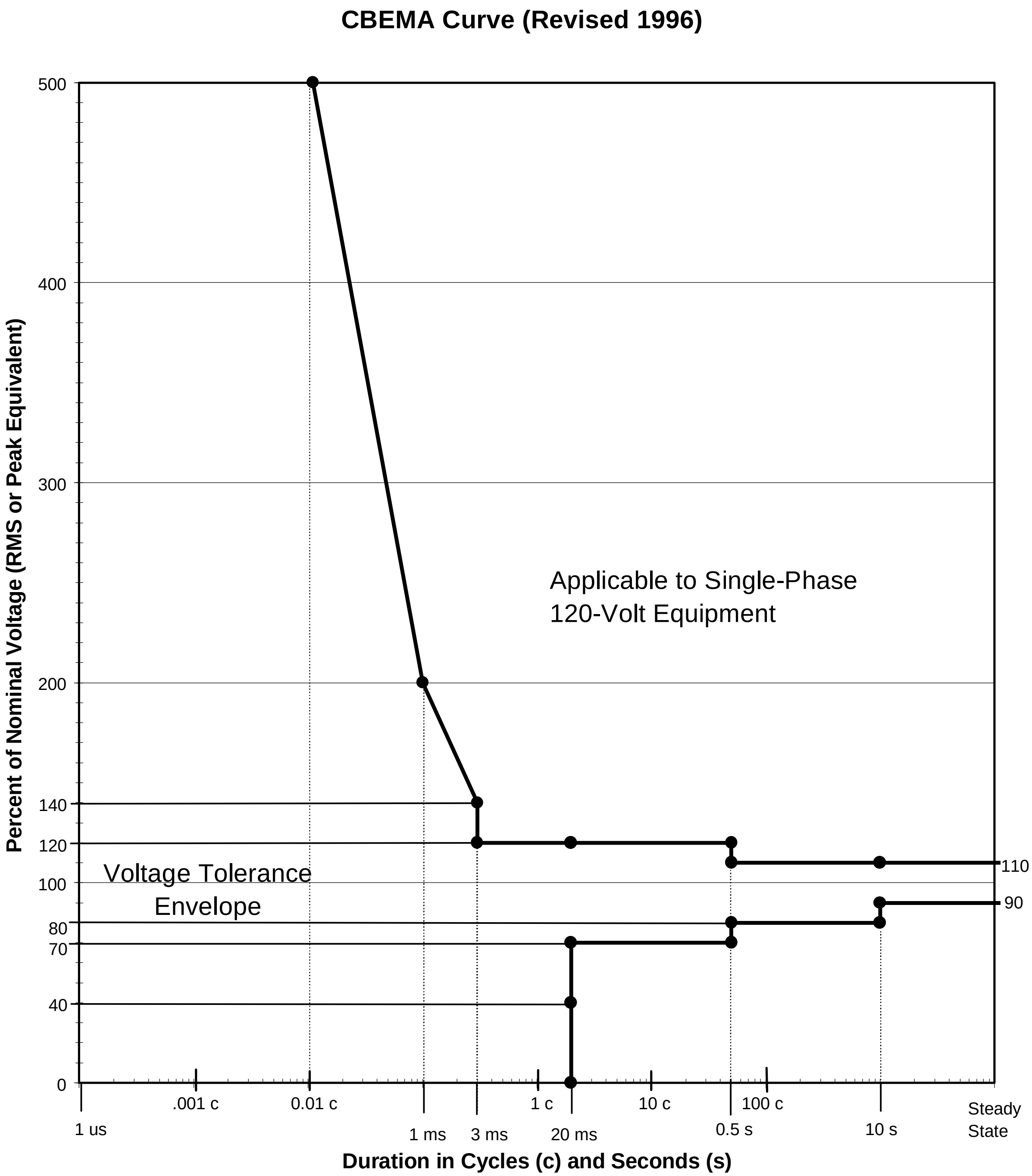

Figure 1-2
Voltage Envelope for Sensitive Equipment [2]

2

PRODUCT MATURATION BARRIERS TO COST REDUCTION

2.1 Basic Performance and Technologies

The power quality mitigation technologies of interest in this report are briefly reviewed in Appendix A. Their development status and the relevant research and technology advances that would move these products toward lower first costs are also overviewed. The technologies are listed in Table 2-1 for reference only.

Table 2-1
Power Quality Mitigation Technologies of Interest in this report

• Conventional UPS • Written Pole MG Set • Dynamic Sag Corrector • Batteries • Flywheels, Low Speed	• Flywheels, High Speed • Ultracapacitors • Superconducting Magnetic Energy Storage (SMES) • Fuel Cells

The single most significant product maturation barrier to cost reduction for most of the technologies listed above is the lack of clearly defined specifications and installation requirements (except the conventional UPS). Whatever the specific design basis, the purpose for the power quality mitigation device is improvement to the electrical characteristics of the voltage as seen by the connected equipment, thereby increasing the productivity of facility operation.

Specifications are essential to purchasing a power quality mitigation product. There are a large number of different specifications that are published by manufacturers. Some of the specifications are of universal importance to all users, and some are of more interest in one application than another. But it is essential that the equipment user's procurement specifications should emphasize those requirements of particular interest for the specific user's application. Any items that can have the specification loosened should be treated appropriately in the procurement. This approach helps to assure that the product is the best combination of performance and price for the requirements of the particular installation. Appendix B contains a generic checklist describing essential specification issues that need to be addressed by the equipment user for a power quality mitigation device.

For the technologies listed in Table 2-1, two time frames of particular interest are the required response time to the disturbance event and the discharge time or duration ride-through time. Typically, for power quality applications a response time of about 1/4 cycle is required to prevent the load from seeing an interruption. All technologies discussed here are assumed to be configured with appropriate power electronic topologies and controls to have this desired response time.

For momentary outages and some levels of voltage sag, real energy must be injected into the electric service supply to prevent a load "upset". The discharge time, or disturbance period to be covered, along with the power level determines the amount of real energy required, which must be stored in some form. This is because power $\times$ time = energy. (Note: system component inefficiencies need to be accounted for and will depend on equipment ratings and load levels actually applied). As indicated in previous studies [1, 3], most power quality events can be protected for in 3 seconds or less. For energy storage technologies, the storage system cost is strongly dependent on, or even directly proportional to, the storage requirement (because of the relationship to discharge time). Thus, it is extremely important not to oversize the storage unit.

A complicating factor may be the stored energy device recharge time. In some systems, energy cannot be restored to the system as quickly as it was drawn out. In these systems, the charging electronics are not the same components as the discharging electronics and are selected to minimize power electronic costs. In either case, if recharge time is slow, and multiple events are anticipated, then more stored energy will be needed. This must be accounted for in sizing and costing the power quality mitigation equipment.

Achieving the desired system output voltage can be a barrier for some products, such as batteries, capacitors, or fuel cells, which are inherently made up of series strings of low voltage elements. These need to be stacked in series or connected in parallel to achieve the voltage and current levels required for boosting. For technologies like flywheels and motor/generators, higher voltage is easier to produce. In many cases, higher output voltage may require more components depending on the manufacturer's particular design strategy. The specific design approach taken by the manufacturer can significantly impact the cost and efficiency of the system.

Table 2-2 shows the typical content of a power quality mitigation system specification with application parameters. If this kind of information were available for each emerging power quality mitigation system of interest, the product maturation barrier for each system would be lowered, thereby facilitating improved application understanding for potential equipment buyers and users.

Table 2-2

Typical Power Quality Mitigation System Specification with Application Parameters

	Application Parameters	**Typical Pillar Triblock Specification**
1	**Output Requirements:**	
2	Output Power	2500 kW
3	Output Active Power	2500 kVA
4	Ouput Voltage	12.8 (12.5-13.2) kV
5	Output Current	113A
6	Maximum Full Load Ride-Through Time	3 Seconds
7	Re-charge Time	Adjustable-Standard Settings at Four Times Maximum Full Load Ride-Through Time
8	Voltage Regulation	± 1% Steady State with Symmetrical Load, ± 8% Dynamic For 50% Load Change
9	Recovery Time	200 ms to ± 2% for 50% Load Change
10	Frequency Tracking Window	60 Hz ± 0.5 Hz to 5 Hz Adjustable

Table 2-2 (continued)

Typical Power quality Mitigation System Specification with Application Parameters

	Application Parameters	**Typical Piller Triblock Specification**
11	Total Harmonic Distortion (THD)	1.5%(Ph-Ph), 2.5% (Ph-N)
12	Overload in Normal Operation	10% for 1 Hour, 25% for 10 Minutes, 50% for 2 Minutes
13	Short-Circuit Current	Approximately 8 x Rated Output Current for 10 ms, 2.5 x rated Output Current for 5 sec.
14	Phase Angle	120º ± 1° with Symmetrical Load
15	Load Unbalance Capacity	50%
16	**Input Requirements**	
17	Rated Voltage	12.8 (12.5-13.2) kV
18	Steady State Voltage Tolerance	+15% to –15%
19	Short Term Voltage Tolerance	-50% for 5 seconds, -20% for 10 minutes
20	Rated Frequency	60 Hz
21	Rated Input Current	102 A
22	Maximum Current (at –25% voltage)	150 A(including 25% charge current)
23	Power Factor	0.94 at Full Load & Nominal Input
24	Harmonic Attenuation	>99% (input to output and output to input)
25	Max. Input Current on Mains Short Circuit	2 x Nominal Input Current
26	Starting Supply	480 V, 3-Phase
27	Power Starting Supply	75 kVA

Table 2-2 (continued)

Typical Power Quality Mitigation System Specification with Application Parameters

	Application Parameters	**Typical Piller Triblock Specification**
28	Powerbridge Voltage	750 V
29	**General Data/Requirements:**	
30	Operating Temperature (Air Inlet to Container)	- 5°C to 50°C
31	Relative Humidity	0% to 90% Non-Condensing
32	Rated Altitude	3280 ft / 1000m
33	Dimensions TRIBLOCK MV Container	
34	Height (Cabinet) w / o Sunshield	3200 mm / 10 ft
35	Width (Cabinet)	10,000 mm / 33ft + 7700 mm / 25 ft
36	Depth (Cabinet)	3000 mm / 10 ft
37	Weight TRIBLOCK System, (incl. container)	55000 kg / 121000 lb
38	Sound Level @ 1 Meter	75 dB (A)
39	Paint Finish	ANSI 61
40	Degree of Protection	IP 54 (NEMA 1.25.8.1)
41	Efficiency: (both for linear and nonlinear load)	%Load / with pf 0.8 / with pf1.0 25 / 89.3 / 89.2 50 / 93.9 / 94.0 75 / 95.2 / 95.5 100 / 95.4 / 98.2
42	Transportability	Complete on Truck
43	Magnetic Levitation Powerbridge	100% Rotor Weight Compensated
44	Approval	Open

Table 2-2 (continued)

Typical Power Quality Mitigation System Specification with Application Parameters

	Application Parameters	Typical Piller Triblock Specification
45	DC Link Voltage	1200 V
46	Lifetime	25 Years (see maintenance)
47	Maintenance	Annual Service (1 day), 8 Year Bearing Change
48	Alarm and Trip Colors	RED: in operation, GREEN: available, YELLOW: not available or fail
49	Protection and Relaying Scheme	Overcurrent and Differential Protection
50	Diagnostic and Monitoring Signals	10 Potential Free Programmable Contacts, CAN and MOD bus
51	BIL Level for the Choke	BIL 95
52	BIL Level for the Generator	BIL 60 (HV arrestors, 8 kV fitted)
53	BIL Level for the Switchgear	BIL 125

2.2 Cost Analysis and Cost Drivers

Power generation technologies and many power system equipment are costed on the basis of power rating, i.e., $/kW. With proper due–diligence, the $/kW can be helpful in arriving at a “rough-estimated” equipment cost, but the following caveats need to be exercised. Virtually all power generation technologies and proven system equipment, no matter what their kW rating may be, have common subsystem components with fixed-costs throughout the product line’s kW range. To illustrate one concern about $/kW numbers, assume identical UPS technology equipment for a 5kW UPS (without storage device) is priced at $4,000 resulting in $4,000/5kW = $800/kW, and a 50 kW UPS (without storage device) is priced at $25,000 resulting in $25,000/50kW = $500/kW. The $300/kW difference may be explained by both UPSs utilizing the same internal controllers, signal conditioning elements, etc., whose fixed-costs when amortized over a lower kW rating reflect a higher $/kW . Also, it is common that mechanical packaging components and internal thermal conditioning are relatively more costly for lower kW systems, which furthermore mirrors a higher $/kW for the lower rated equipment. Another concern for using $/kW figures indiscriminately, is that different manufacturers of equipment with identical kW ratings frequently have different equipment design and application strategies that can vary $/kW costs by as much as two to one. And still another caution for using $/kW numbers is “how the particular power system boundaries are being defined?” Does the system $/kW include any input/output isolation components? Are there other electromechanical control devices required for equipment operation and/or protection? Each of these concerns can be alleviated when clearly defined specifications and installation requirements are the basis for the $/kW cost analysis.

Many of the technologies discussed in this study involve storage devices. While this further complicates costing on a $/kW basis, if done with care, the exercise can be informative. The only meaningful way to make direct comparisons between different storage technologies is to evaluate costs for similar discharge times. Again, the best approach is to specify the system parameters (power rating and discharge time) and then compute equipment cost. Following is a simplified example to illustrate one method of cost analysis:

Power Quality Mitigation System Cost (dollars) = Cost of Power System Equipment + Cost of Energy Storage System + Cost of Other System Elements

Figure 2-1 shows a representative power quality energy storage system (in this case, a flywheel system) and the system components. The component costs are addressed separately in the following sections.

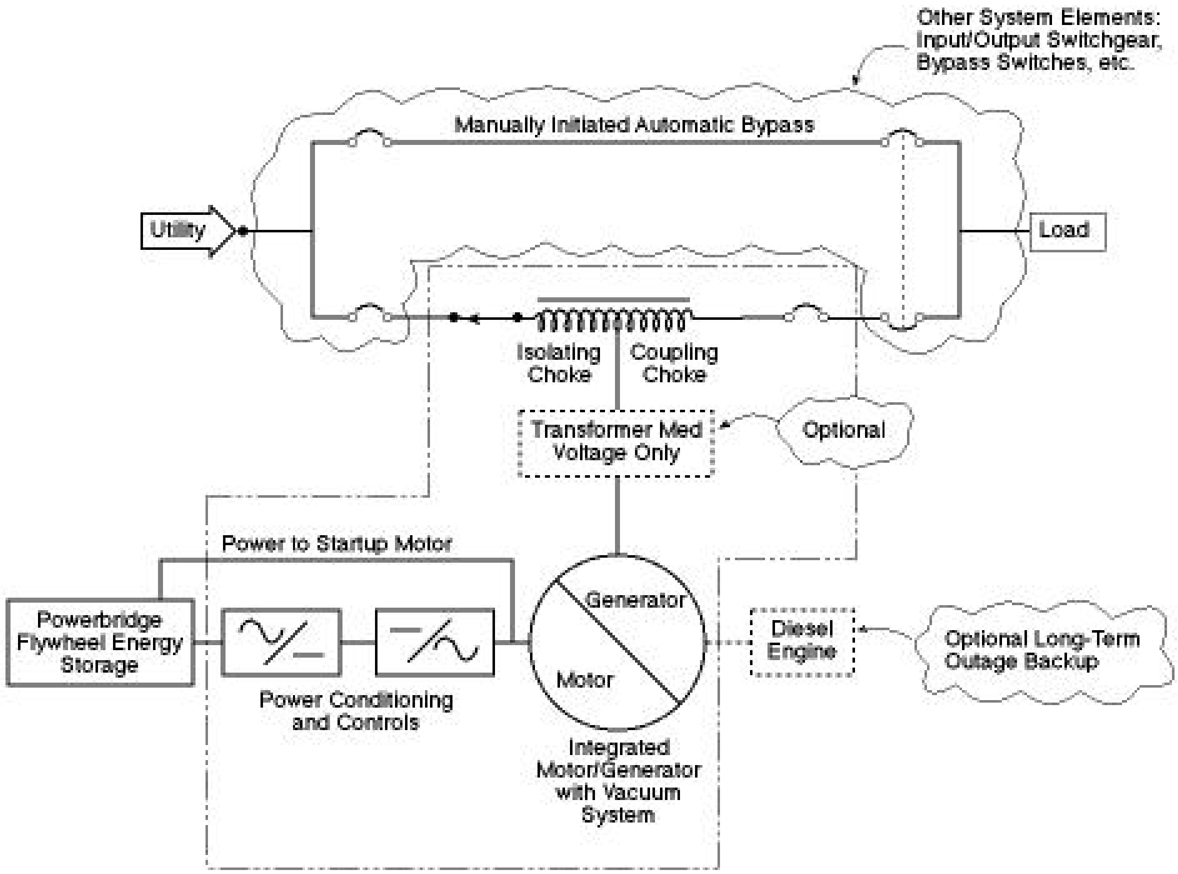

Figure 2-1

Example of Power Quality Energy Storage System Showing Typical System Components

2.2.1 Power System Equipment Costs (without Energy Storage)

The primary cost drivers for power system equipment are power level, interface voltage levels, performance features, and duration of operation, which can determine the method of temperature control required. The cost of power conditioning and control is dominated by the solid-state switches and the desired output characteristics, especially voltage. Above a few hundred kW, generally, the unit cost ($/kW) of power system components will be nearly constant, and the system cost will simply scale with power level.

Estimated Cost of Power System Equipment (dollars) = Power Rating (kW) × Unit Cost ($/kW)[1]

Note: [1] Refer to the cautions described in Section 2.2

If the power system equipment has to interface with a higher utility/load voltage level, it may require the use of a medium voltage isolation transformer with its added cost. Also, if four-quadrant (VAR) control is required, the additional control devices and components to accomplish the desired operation will increase equipment costs.

It is noteworthy to mention here, that with any power system equipment, thermal management is always required and is directly related to how the equipment is operated. The method of controlling equipment heat removal include water-cooling, forced air, natural convention, and so on [4]. Each cooling method has its pros and cons, and can effect equipment costs, equipment reliability, equipment maintenance expenses, floor space required, etc. In some cases, these costs may not be trivial, therefore thermal management schemes should be discussed with equipment suppliers during the equipment specification development period.

2.2.2 Energy Storage Component Costs

Considering the energy storage component costs, each type is governed by different physical principles (kinetic energy, chemical energy, magnetic energy, etc.) and the cost of each ($/kWh) scales somewhat differently with storage capacity. For many of the newest technologies, more energy is provided by simply connecting more modular units together. Table 2-3 below gives a brief view of the storage principle and cost scaling $/kWh for each type of storage medium of interest in this study.

Table 2-3
Energy Storage Components: Physical Principles and Scaling

Type of Storage	Storage Principle	Cost Scaling ($/kWh)
Flywheel / Motor Generator	Kinetic Energy (rotation)	Modular, Unit Cost Improves somewhat with Size (energy)
Ultracapacitor	Electrostatic Capacitance	Linear with Size (energy)
SMES	Magnetic (induction)	Unit Cost Improves Greatly with Energy if Modular Units are NOT Used
Batteries	Electrochemical Potential	Linear with Size For Discharge Duration of 1 Hour or Greater
Fuel Cells	Fuel Storage (Hydrogen, Hydrocarbon or Hydride)	Improves somewhat with Size (energy)

In the worst case (batteries, capacitors) energy storage costs scale nearly proportionally with storage capacity because identical "cells" are combined to meet the desired energy storage. Depending on how innovative the paralleling and series mechanical connection technology is will determine the extent of additional losses.

Estimated Cost of Energy Storage System = Stored Energy (kWh) × Unit Energy Cost ($/kWh)[1]

Note: [1] Similar cautions described in Section 2.2 for power system equipment costs are applicable to energy storage system costs. It's best to discuss these issues with each storage system manufacturer during the equipment specification development period.

In the best case (SMES), costs can scale with energy to the 2/3 power, if a larger magnet is wound for larger storage capacity [5].

$$\text{Cost of SMES} \propto \text{Energy}^{2/3}$$

In most power quality mitigation system applications, the cost of the power conditioning and control electronics may be a significant part of the system cost. This cost will vary from manufacturer to manufacturer as previously discussed in Section 2.2, but may be more influenced by the application parameters and system specifications required for the specific installation. Also, because the storage cost can scale linearly with time, as discussed above, it is important not to oversize the storage unit by specifying a longer discharge duration than necessary. For example, the capacitor portion might be 50% of the cost an ultracapacitor system designed for 5-second discharge. If the specification is revised to request 10 seconds at the same power level, the equipment will now cost one-and-a-half times as much.

2.2.3 Equipment Costs vs. System Cost vs. Installation Cost

Individual storage units and power system equipment do not add up to the entire system cost. A totally integrated system will include input/output switchgear, possibly a by-pass switch, and a user interface, which may include remote monitoring and data acquisition system (see Figure 2-1 for a typical totally integrated system). Other items could include auxiliary thermal management equipment (water-cooling, air conditioning), packaging or cabinets, and special safety equipment. These items can drive the aggregate cost well beyond the initial individual equipment cost estimates for storage and power system equipment. Some equipment manufacturers include these items in their cost estimates and sometimes, especially if there are optional features, these “other system elements”costs are extra.

Beyond power quality mitigation system cost, which usually means as delivered to the customer site, is installation cost. Additional installation costs can be relatively minor, as for a “trailerized” SMES or most flywheel systems. When installed within a facility, additional costs can be incurred for such activities as installing cables, pouring concrete, moving walls, and adding electrical outlets, modem lines, or safety signs. In order to get a “better handle” on these costs, it would be prudent to include preliminary sketches for the proposed equipment installation, and to develop budgetary materials and labor requirements for use in estimating total project cost. Hand marked drawings and sketches should be prepared to better understand any installation issues of concern. Included should be a one-line electrical diagram of how the proposed power quality mitigation system will “fit-into” the facility. Approximate site location of equipment layouts, proposed cabling and wiring routing with ratings, and conduit and cable tray sizes. Include proposed system control interface with the facilities operations center. From this information, estimate a bill of materials with labor costs to the best of your ability. Anticipate that the cost trends in moving from equipment to system to full installation will be as indicated in Figure 2-2. The cost trend with increasing output voltage is also shown.

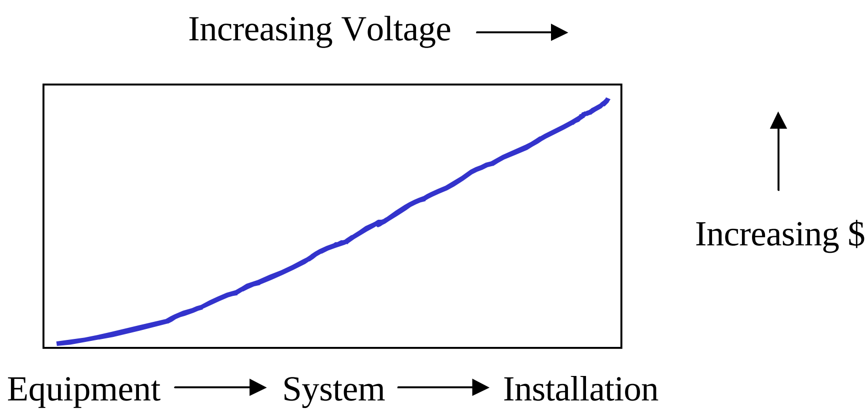

Figure 2-2 Costs for Power Quality Mitigation Systems Increase with Voltage and Degree of System Integration

2.2.4 Life Cycle Cost

Beyond capital cost for all power quality mitigation systems is another consideration: the life cycle cost. Components of life cycle cost are carrying charges for the capital equipment, fixed operating and maintenance costs, and variable operating and maintenance costs. Included in the variable cost is the cost of charging electricity to recharge the storage system and to keep it ready between discharges. This will differ for each technology because of differing energy efficiencies or losses, and differing parasitic energy needs. Batteries, for example, require trickle charging, flywheels have losses due to bearing friction, and SMES operates with a continually running refrigeration. Also included in the variable cost is the replacement cost of system components with relatively short life, such as some battery cells. Thus, the different systems have very different operating and maintenance (O&M) requirements in addition to varying up-front capital costs. In fact, many of the more advanced technologies were specifically developed to get away from high O&M costs and problems with lead-acid batteries. Table 2-4 presents a brief comparison of life-cycle issues for the various power quality mitigation system products.

Table 2-4
Comparison of Life Cycle Issues for Power Quality Systems

Technology	Cycle Life / Life	O&M	Parasitic Energy Requirements / Losses	Other Issues
Motor / Generator	Good	Medium	Medium	Rotating Parts Replacement
Flywheels	Good	Low	Low	Bearing Replacement
Ultracapacitor	Good	Very Low	Low	String Balancing
SMES	Good	Medium	Medium	Refrigeration Life
Batteries	Poor	Medium	Medium	Toxic Disposal
Fuel Cells	Moderate	Moderate	Relatively High	Fuel Cost Additional
Dynamic Sag Corrector	Excellent	Very Low	Very Low	Electrolytic Capacitor Replacement

2.3 Cost Reduction Opportunities

The costs of various technologies can be expected to decrease in the future due to three major factors:

1. Technology improvements through R&D,
2. Design for manufacturability and marketability, and
3. Volume production / learning curve economies.

These factors can have a dramatic impact on any industrial product, and especially for those technologies that are new and in limited production such as: high-speed flywheels, ultracapacitors, SMES, fuel cells and Written Pole generators. For these, both technology improvements and mechanical packaging design innovations will make manufacturing easier and thus less expensive and will produce initial cost reductions.

Products which are more mature (low-speed flywheels, batteries, UPS systems) will be driven to lower cost mostly by volume production, rather than by significant changes in manufacturing procedures, or through technology advances, although improvements are always anticipated.

2.3.1 Technology Advances / R&D

Research and development with technology advances often can lower the cost of power quality mitigation system products. Examples are found in the use of new materials or materials processing [6]. Some specific technology advances that will lead to cost reductions are presented in Table 2-5 below.

Table 2-5
Some Technology Advances to Reduce Cost of Power Quality Mitigation Systems

Power Quality Mitigation Product Type	Significant Technology Advances Needed to Reduce Cost
Conventional UPS	None
Written Pole MG Set	Magnet Production Optimization
Dynamic Sag Corrector	Low Cost Capacitors
Low-Speed Flywheel	Modified High Voltage Circuit Configuration
High-Speed Flywheel	Bearings, Rotor Material Optimization
Ultracapacitor	Materials Optimization
SMES	Higher Current Conductor, Larger Winding Configurations, More Use of HTS
Lead-Acid Batteries	None; Mostly Manufacturing Issues
Advanced Batteries	Reactant Optimization, Cell Designs
Fuel Cells	Scale-up in Cell Design, Stack Materials and Configurations; Storage; Hydrogen Production

2.3.2 Design for Manufacturability and Marketability

In the U.S., a new product is often the result of laboratory research or a custom design for a specific customer application, such as a scientific experiment or military system. For these customers, cost is often a secondary consideration after meeting performance requirements. For such a product to reach commercial maturity, it often has to be redesigned so that it can be manufactured in large quantities in automated fashion for the consumer market, and so that the manufacturing process must be standardized and use inexpensive materials wherever possible.

Designing for manufacturability and marketability in a large company is typically done hand-in-hand with the manufacturing and marketing departments. Since small companies usually don't have this expertise, they must rely on published approaches to optimize their products. Economic considerations include product cost factors, "other" factors (described below), and market trade-offs.

Quoting from the "Design for Manufacturability Handbook"[7], product cost factors include: materials, direct labor, indirect labor, special tooling, perishable tools and supplies, utilities, and invested capital. The interrelationship of these variables is considerable, and therefore, a comparison of alternatives must be detailed and complete to assess properly their full impact on total unit costs. Other factors include costs related to packaging, shipping, service and unusual maintenance. To the extent that any of these factors differ between alternative manufacturing methods, the entire product can be optimized to minimize cost.

Designing for manufacturability is not done capriciously. Some basic principles for designing for economical production include [8]:

1. Simplicity

2. Standard materials and components

3. Standardized design of the product itself

4. Liberal tolerances

5. Use of the most processible materials

6. Teamwork with manufacturing personnel

7. Avoidance of secondary operations

8. Design appropriate to the expected level of production

9. Utilizing special process characteristics

10. Avoiding process restrictiveness

In addition to designing for manufacturability, it is important to design for marketability. Some of the "other" factors above come into play here, as well as more subtle features. Marketability means being able to judge what customers consider as high priority when selecting a product. Beyond cost, there are many features, such as size and shape, ease of connection and use, ergonomic aspects and others. Design researchers have determined that a final product design should not be established until several market "concepts" have been tested [9]. This adds to the product development time, but can ultimately improve market size.

Many small businesses are not really equipped to optimize design without outside help, because they don't have "mass production" manufacturing departments (yet). Fortunately, there are companies who do exactly this type of product design optimization. An example is IDEO, a spin-off from Stanford University, which has many successful consumer products to show for its effort.[10] Unfortunately, these services are not inexpensive, and so the whole design process becomes part of the product cost optimization.

2.3.3 Volume Production / Learning Curves

Technologies that are amenable to standardization and to the exploration of economies of scale tend to follow a learning-by-doing pattern; increased productivity, and thus lower specific production costs, result as a function of cumulative production or life cycle stage. Their performance, and in particular their production cost, can be said to follow a learning curve.[11] As others have observed, the shape of such curves suggests that the cost reductions due to learning effects can be modeled to a zero order as:

$$C = aP^{-b}$$

Where C is the unit production cost, P is the cumulative production and *a* and *b* are constants. *a* is the cost of the first unit.

The effect of *b* on the rate of cost reduction can be seen by observing that

A value for *b*:	**leads to a cost reduction for each doubling of cumulative production of:**
0.10	7%
0.20	13%
0.30	19%
0.40	24%
0.50	29%

Figure 2-3 shows typical learning curves. The historical cost data as a function of cumulative installed capacity (MW) for solar photovoltaic (PV) modules and gas turbines imply values for *b* of about 0.30 for PV solar cells and early gas turbines, and a little below 0.10 for mature gas turbines. The gas turbine example shows two different sections of the learning curve: first, the early cost decline as a result of RD&D experience and initial economies of scale effects, and second, later post-commercialization cost improvements. Anticipated exponents are 0.415 for advanced flywheels [12] and approximately 0.2 for fuel cells [13].

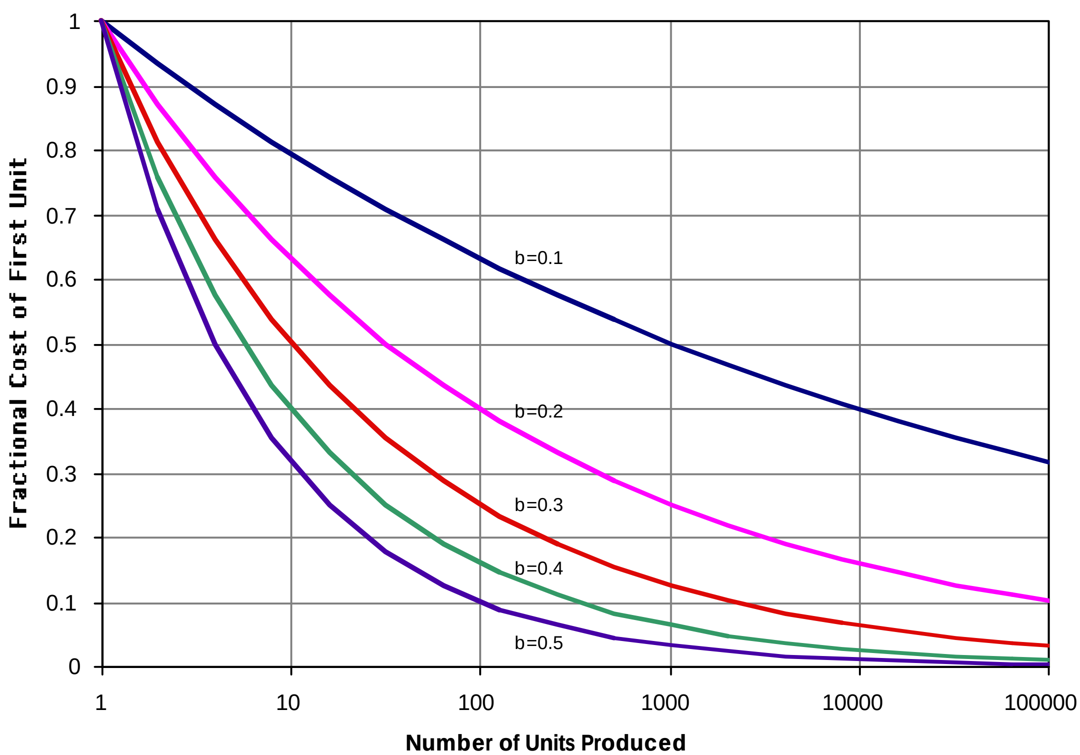

Figure 2-3
Typical Learning Curves

2.3.4 Summary of Costs and Projected Costs

Based on discussions with equipment manufacturers and a review of the literature, the costs of the various technologies investigated are summarized in Table 2-6 below.

Table 2-6

Power Quality Mitigation Product Costs and Projected Costs

Product	Current Price ($/kW)	Projected Price ($/kW)	Cost Driver
Conventional UPS	600-700	500-600	Volume Production
Written Pole MG Set (15 sec)	1100	≈ 700	Volume Production
Dynamic Sag Corrector	184	≈ 150	Components, Volume Production
Low-Speed Flywheel (15 sec)	265-400	200-300	Volume Production
High-Speed Flywheel (15 sec)	750	250-400	Bearings, Material Development, Volume Production
Ultracapacitor (10 sec)	≈ 1000	500	Manufacturing Procedures, Volume Production
SMES (4 sec)	200-600	200	Design Configuration, Cryogenics, HTS, Volume Production
Power Quality (Lead-Acid) Batteries (30 sec)	350	200	System Integration
Advanced Batteries (1 hr)	≈ 2000	≈1000	Reactant Optimization, System Configuration, Volume Production
Fuel Cells (Premium power)	≈ 1500	500	System Design, Volume Production
Fuel Cells (Dynamic response)	28,000	≈ 1000	System Design, Component Development, Scale-up, Volume Production

2.4 Specifications and Standards

A major barrier to maturation and commercialization of new power quality mitigation system products is the lack of routine specifications and established standards. Although the general requirements for a "typical" system were listed in Table 2-2, these do not constitute strict specifications, especially in that tolerances are generally not consistent from one project or customer to the next. Only a few power quality mitigation system manufacturers publish and distribute specifications for their established products, with model numbers and routine ordering procedures. Many systems are only available on a one-or-two-of-a-kind basis, with a different set of specifications for each follow-on system. It would be useful for the power quality community to establish a set of functional specifications to be stated for each power quality mitigation system product, regardless of its physical principles. (Examples of specifications are found in the Appendix B, illustrating the spectrum from minimal to detailed specifications.)

Furthermore, there are few standards, such as IEEE, UL, CIGRE, IEE, or even MIL standards that currently are applied to new power quality mitigation system products. This is changing with UL listing of the Clean Source flywheel system [14] and drafting of IEEE PAR 1547: "Standard for Distributed Resources Interconnected with Electric Power Systems" [15], but much remains to be done. It is likely that when standards are established and adopted, that some products may actually become more expensive in meeting these standards, before standardization helps to bring costs down by establishing constraints in early design work. Safety standards and procedures, aside from performance standards, are still being adopted for many of these technologies.

2.5 Small Business Culture

Product maturation is often stymied in a small, high-tech start-up business by the very nature of small businesses. This is true throughout most types of small businesses (including information companies, etc.), but is especially true for high-tech industrial products for several reasons.

1. Staff skills are often highly technical, focussed on innovative physics, chemistry, engineering, or materials disciplines. While this is ideal for inventing or discovering revolutionary solutions to power quality problems, it may not be the right skill set for overcoming (mundane) manufacturing barriers or addressing marketability, as discussed above. This can make it harder to address cost reduction issues and strategizing for market volume. In addition, a small business often cannot afford the needed skills to move from science and engineering to market.

2. Many small businesses are launched on funding from government agency small business innovative research (SBIR) grants. These contracts are focused on the initial innovation and provide limited motivation to move to volume production.

3. Many engineers and scientists in small business usually have no work experience on the plant floor in the types of facilities where their products will operate. This lack of intimate experience and knowledge of applications and customer concerns can also hamper design for “marketability”.

4. “High tech” solutions are the hallmark of many new small businesses, especially those launching innovative industrial products. Motivation for the product comes from inventing a better mousetrap. Sometimes such products are more expensive, however, than the old mouse trap, and justifying the innovation can be difficult. The bright personnel who invented the more sophisticated approach may not be interested in working on something less sophisticated.

5. Business issues can also sometimes trip up a small business, especially as it grows, since new policies and procedures often need to be established. Routine business practice, such as setting up a contracts office to deal with customer purchasing agents, may prove an obstacle in small businesses.

All of these reasons can serve to slow the move to volume production and its accompanying cost reductions.

2.6 Financial Considerations

New product development usually requires financial support for a period of years until a commercial return on investment is expected. Start-up companies, and even mature companies, launching new products must spend considerable effort to secure funds for product development. This has two damping effects on eventual cost reduction. First, the time and energy involved in financing takes away from product engineering work. It can also cause a cycle of down time for personnel while money is being sought. Second, the cost of development is often buried in the price of the first units, as companies seek to recover these costs and possibly repay loans or other investments. Thus, initial units not only are more expensive because manufacturing and production economies are not being realized, but because of buried investment costs.

3

MARKET BARRIERS

In general, high-technology power quality mitigation system solutions are not well understood by utility and customer personnel, and are presently perceived as being much higher in cost than conventional power quality solutions. In this section, market barriers are presented that need to be overcome to raise the sales volume for these power quality products. Six (6) relevant market barriers discussed are listed in Table 3-1 and overviewed in the following paragraphs.

Table 3-1
Six Most Relevant Market Barriers

1. Conservative Customers / Mature Vs. New Products	2. Unknown Value of Benefits / Difficulty in System Specifications
3. Product Familiarity and Competition	4. Cost
5. Deregulation: Electric System Restricting	6. Financial / Contractual Agreements

3.1 Conservative Customers / Mature vs. New Products

Most power quality mitigation system technologies are new products with relatively little documented field experience. This is a definite barrier to most potential customers who want only to purchase tried and proven system equipment and hardware. Sometimes perceived safety concerns or lack of standard specifications, such as UL listing, can be an insurmountable barrier. Fortunately, a few utility and industrial customers are less risk-adverse and are willing to try new technologies, even at the prototype stage. A number of such projects are made possible through cost sharing arrangements with sponsoring agencies, such as EPRI and the Department of Energy.

3.2 Unknown Value of Benefits / Difficulty in System Specification

For utilities and their customers who perceive a power quality need, there is little comprehensive data to establish the value of benefits for installing such systems. The most useful information is often derived from determining what such problems cost the customer, i.e., what is the cost of lost production, down-time, or clean-up if a production or processing facility is shut down because of a voltage sag or outage? How often does it actually happen? Whereas there may be workers who have some idea of these data, there is rarely a quantitative record on which to base a cost/benefits analysis. Often a procurement decision will be made simply to avoid the nuisance of a shut down.

Furthermore, without actually monitoring the power into the facility and recording the duration of events, it is difficult to determine how long a power quality system would need to carry-over. Many potential customers take a conservative approach and ask for 15 to 20 seconds, when, in fact, they may only need a second or two of ride-through. The 15 to 20 seconds' value can mean a much more expensive system than is really needed. On the other hand, transition to back-up power frequently requires up to 15 seconds.

Certain customers could be satisfied by protecting only their most critical loads. However, knowing which parts of a total plant are critical may require some study. In successful power quality installations to date, utility sponsors or equipment manufacturers have worked to determine which are the critical loads, the power level, the duration and the depth of voltage that can satisfy the customer's needs. To successfully compile the optimum power quality mitigation system specification, a thorough analysis of the power system and loads should be conducted to define the areas of concern as accurately as possible before attempting to solve the problem. Coordinate involved parties, the equipment user/owner, electronic equipment manufacturer/supplier and discuss the objectives of compiling basic costs. This approach can enable cost-effective solutions to be implemented that not only correct the existing conditions but also minimize future problems.

The key is to understand and define the problems, and to estimate cost impacts before attempting to solve them. Effective communications are essential to determine proposed solutions and their basic costs. Following is a checklist to walk through the process of gathering information.

(•) ***Identifying what sensitive electronic equipment is experiencing problems (e.g., type, location).*** While the operators of the electronic equipment are primarily concerned with the productivity of the equipment, they need to be made aware to report that the equipment is not performing as intended and it is costing the company money.

- (•) ***Document the types of equipment malfunctions or failures (e.g., data loss, lockups, and component damage).*** Arrange to meet with equipment users to establish objectives of compiling basic costs associated with loss of production and increased operating expenses. While technical details on power disturbances are normally of little interest to the end-user, it is important that they provide their best feedback on equipment upsets.

- (•) ***Determine when do the problems occur (e.g., time of day, day of week, particular system operation).*** Valuable information to solving facility power problems and compiling basic costs is keeping an accurate log of equipment errors and malfunctions. An effective method to document this kind of information should include meetings between the facility manager and local electric service provider personnel. In this way, site-specific information on disturbances that occur on the utility distribution system can be related to the site's internal power anomalies. As these issues are discussed between both parties, this is an excellent opportunity to develop insights to such items as the value of loss production and/or the end-user's methodology to establish the company's basic costs of power quality impacts.

- (•) ***Establish those coincident problems occurring at the same time (e.g., lights flicker, motors slow down)***. Single observations such as these provide valuable clues to identify possible problem sources and PQ impact basic costs at the site. For example, perhaps a large horsepower induction motor being started "across-the-line" seems to be creating a current surge resulting in a perceptible lighting system flicker. Armed with documented symptoms like this, intelligent and probing questions can be directed at the electrical equipment suppliers to determine what the most cost-effective solutions might be.

- (•) ***Investigate possible problem sources at site (e.g., arc welders, air conditioning, copy machines, and any equipment with rectifier input power supplies).*** This approach involves gathering equipment power quality immunity and emissions guidelines from equipment manufacturers or testing labs such as the EPRI PEAC Corporation where equipment is characterized to determine immunity and emissions to voltage sags, impulse transients, system fault responses, and harmonics environment. Equipment power quality "performance envelopes" are essential to accomplishing evaluations on basic costs for production and/or services impacts.

(•) ***Make inquiries regarding existing protection for equipment (e.g., transient voltage surge suppressors, isolation transformers, internal electrical filtering circuit devices, etc.).*** The job of compiling basic costs and selecting power-enhancement vary for many reasons. One frequently ignored factor is that the equipment's own internal PQ protection or filtering may be dysfunctioning, or interacting with other electronics-based loads.

Combining the aforementioned gathered information with the range of available technologies and the different power quality options offered by equipment suppliers can make compiling power quality mitigation system specifications a straight-forward process. Any meaningful efforts to define your power quality equipment needs more accurately can be a beginning in overcoming cost barriers for the equipment procured.

3.3 Product Familiarity and Competition

Another apparent barrier to sales of some power quality mitigation systems is confusion on the part of potential customers as to which system is right for their needs. In the past few years, numerous new, unfamiliar products have appeared on the market, through trade shows, trade literature and conference events, all claiming to be the solution to power quality needs. While some do, in fact, compete directly with each other in performance and perhaps cost, many actually serve varying needs, covering the spectrum of power quality sizes and functions. A lack of clear distinction through detailed technical specifications and credible documented performance comparisons make it difficult to select a suitable product.

3.4 Cost

High cost is definitely a market barrier. Most utility and industrial customers look at the standard battery-based UPS for cost comparison. These can range in cost from $200/kW to $700/kW, depending on capabilities. For some advanced power quality mitigation products, it is difficult to compete unless they fall in this range, and many are not there yet. As explained in Section 2, simple cost comparisons can be inadequate for accurate screening of potential solutions because some offer longer duration carry-over and other features that may be "over-kill" for mitigating the existing power problem. Nonetheless, this type of screening is done routinely. Therefore, this range sets a target for new emerging power quality mitigation products.

3.5 Deregulation: Electric System Restructuring

Deregulation has had contradictory impacts on the power quality market. A negative impact has been internal restructuring at many utility companies, such that there are few remaining personnel familiar with power quality problems, let alone the potential solutions. This situation leaves a big void for equipment manufacturers – with whom should they meet in order to convey the features of their products? It also leaves a void for utility customers in search of solutions. A further negative is that with multiple energy suppliers, distinct from the distribution companies, sometimes it is hard to determine who is responsible for disruptions and for mitigating against them. The confusion in this aspect of the market is slowing the entry of cost-effective power quality solutions.

A positive aspect is the opportunity for energy suppliers and distribution companies to use power quality as a special service or product. A true revenue center is possible, although this model has not proven successful so far. It appears that those utilities in, or contemplating entering into power quality-related businesses are finding that they are trying to sell something that their customers thought they were already paying for – *quality power*. For those end-users who have not had a power quality related problem, this is certainly their expectation, and in their view, a fact (everything works). Those customers who represent a significantly large portion of the utilities revenue will probably expect, and be in a position to demand, a high level of quality of the delivered electric supply as well as some level of power quality troubleshooting service from the utility “free of charge.”

Distributed generation proliferation could be either an opportunity or a barrier for power quality mitigation system product manufacturers. The impact of this addition to the electric system is not yet known or easily projected. Will it improve distribution power quality, or degrade it? Can distributed generation be enhanced by incorporating energy storage / power quality enhancement systems? The answer to the last question is likely yes, but it may be some time before the market develops, since distribution system and customer electric service interface issues are being addressed slowly.

3.6 Financial / Contractual Arrangements

The procurement of power quality mitigation systems or services can be accomplished in a number of ways. Historically, electric system equipment is purchased as a capital expense. This can be expensive and difficult to justify for new types of equipment in somewhat experimental settings. Other options include leasing, which has become popular, and service agreements. In the latter, monthly or annual service fees cover the cost of the equipment, including O&M costs. Such charges can then be included in an operating budget. Over time, this approach may cost more than outright purchase, but is often covered by a different budget.

When provided by the energy supplier, such a service fee could be translated to a higher electric rate per kWh. This approach has been tried in unregulated situations, but has yet to be approved under established rate structures. Yet another approach is more like an insurance policy, in that regular payments ensure a specified level of service or power quality and the electric service supplier is responsible for providing that power, regardless of the equipment required. This last option is being used in at least one premium power / power quality park setting. Although there exist these many financial possibilities, the lack of an established and well-documented process can make it difficult for a potential customer to settle on an approach and make a commitment to a power quality mitigation system installation.

4

BREAKING THE MARKET BARRIERS

This brief section attempts to address the market side of the cost reduction equation by highlighting activities that can help drive the market. Six (6) possible methods to overcome cost reduction barriers are listed in Table 4-1 and are discussed in the following subsections.

Table 4-1
Six Possible Methods to Overcome Cost Reduction Barriers

1. Education: Utilities and Customers	2. Demonstrations for Experience and Visibility
3. Business Models: Service or Products?	4. Building Competition
5. Accelerating Production to Reduce Cost	6. International Considerations

4.1 Education: Utilities and Customers

One successful activity for overcoming market barriers is to educate potential customers. Utilities and their customers need to be made more aware of the value and applications of power quality mitigation systems, the differences among them, and the experience being gained with various systems. These efforts should be accomplished jointly with power quality mitigation system manufacturers. Such education takes place at professional conferences, at trade shows, and at targeted workshops. Technical literature can provide information and data at varying levels of complexity, and of course, much information is now available on the World Wide Web. EPRI plays a significant role in the education component of market visibility for power quality mitigation system products.

4.2 Demonstrations for Experience and Visibility

Whereas industry and private or government sponsors often take responsibility for product demonstration at the laboratory, shop floor, or prototype stage, it is equally important to demonstrate applications in the field so that potential users see successful system operation. Demonstrations can evolve experienced manufacturers and users, and also provide opportunities to increase visibility and product familiarity. This may require more than one successful field application demonstration. Financing for these early installations is usually a joint effort of the equipment manufacturer / developer, user, and outside sponsor, such as EPRI and / or a host utility.

4.3 Business Models: Service or Products?

It would be useful to investigate the various business models followed by system manufacturers in making contractual arrangements with their customers, in order to understand which approaches are proving most successful. Should power quality be considered a service? Or a product? While this information may be confidential for individual relationships, an overall view might clarify this issue in the marketplace and move the business along in a definite direction.

4.4 Building Competition

Whereas competition can sometimes be deemed a negative factor for an individual company or product, competition is a good thing for customers, and overall a good force in building a market for a certain type of product. When there are several alternatives, customers may see this category of product as established and useful, and may be more likely to initiate a purchase or other agreement. In the long run, competition is usually good for refining products, market strategies and marketing approaches, in addition to driving prices to their fair market value.

4.5 Accelerating Production to Reduce Cost

Sometimes a purchase of multiple units or systems can jump-start a new product's production line and begin the volume production learning curve for a new product. This type of activity may need to be orchestrated by a focussed interest group, such as EPRI, or an agency with an interest in accelerating the availability of some product type. An equipment manufacturer can sometimes accelerate production by teaming with (or being bought out by) another, perhaps larger company, or by buying out another's production facilities. Both of these actions have occurred within the power quality mitigation system equipment industry in the past year. Accelerated production is the best way to cost reduction for most technologies, as suggested by the visual graphic illustrated in Figure 4-1 below.

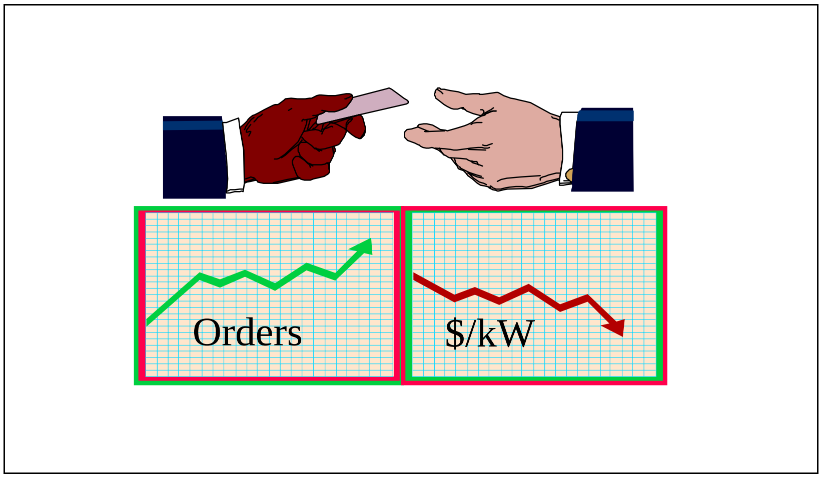

Figure 4-1
Volume Production Drives Costs Down

4.6 International Considerations

Finally, it may be that the largest markets for certain products are not in the U.S. but overseas. Targeting international markets for early sales can also accelerate production, bringing costs into an attractive range for the U.S. market. Some examples are the Dynamic Sag Corrector, low-speed flywheels, and advanced batteries. In addition, overseas production may also be less costly, both with respect to delivery to foreign customers, and with respect to labor costs, as for many mass produced items. On the other hand, some components of power quality mitigation systems require fairly sophisticated processing and quality control, and this may be better achieved under local supervision.

5

CONCLUSIONS

Power quality mitigation systems are available today in numerous types and sizes and with varying functionality. A fair number of units have been demonstrated in the field; some are fully commercial products, and others are in prototype stages. Costs vary widely, but are trending downward. Cost reduction, while it is helped by technology advances, improved design, and constructive business attitudes, is best accomplished through clearly defined equipment specifications and documented installation requirements, and increased volume production. Equipment specifications are essential to purchasing the “proper” power quality mitigation product. The procurement specifications must emphasize those requirements of particular interest for the intended applications. Volume production will come with standardization, but requires large market potential. Driving the market, in turn, requires education and an emphasis on raising the visibility of successful systems. Developers, users, and sponsors must all work together to bring power quality mitigation system technology to full utilization.

6

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A

APPENDIX: TECHNOLOGY STATUS

This appendix lists development status of the power quality mitigation technologies of interest in this study and briefly discusses some R&D or technology advances that would move these products toward lower cost.

Conventional UPS

Uninterruptible power supplies (UPS) are a broad category of technologies utilizing conventional methods of providing protection to loads for both voltage sags and longer duration interruptions. The technologies virtually all employ batteries for the energy storage to provide ride-through. The duration of the ride-through support available is determined by the ratings of the batteries and power electronics applied with each unit.

Written Pole MG Set

Several standard Written Pole products have been commercially available for years. Newer systems are maturing through innovative magnetic materials and production, and through improved design and assembly procedures. Volume production will help reduce costs.

Dynamic Sag Corrector (DSC)

The dynamic sag corrector provides only several cycles of carry-over. Energy is currently stored in electrolytic capacitors. Someday ultracapacitors may replace these. The remainder of the system is configured of power electronic components, and as ultracapacitor costs come down in price, so will the DSC.

Flywheels

Low speed flywheels are a fairly mature technology. Bearing improvements are always welcome because this component limits system life and drives maintenance costs. Also, systems are moving to higher voltages. High speed flywheels, on the other hand, are new, based on revolutionary composite technologies, winding configurations, and stabilization approaches. Most systems are hand produced, and standard products are beginning to become available. Cost savings should result from optimization of high performance materials, bearing and wiring improvements, and design standardization.

Ultracapacitors

Ultra- or supercapacitors are also a new technology. Some use fairly exotic plate materials which are expensive. If the need for these materials can be minimized or eliminated, this reduces the energy storage cost. Also, most are currently made either by hand or in only semi-automated manufacturing processes. When these production techniques become more fully automated, system costs should fall.

SMES

Superconducting magnetic energy storage has made tremendous technology advances over the past ten years. Cryostat technology has been standardized and dramatically improved to minimize refrigeration requirements and parasitic electric load. Winding processes are still not automated because of the small number of magnets produced each year. This should improve with volume production. Power leads have been transformed by the use of high-temperature-superconducting (HTS) materials, so that these are now nearly standard items. Refrigeration affects the operating cost, and the capital cost for the refrigeration system. Further advances in HTS superconductors could eventually lead to entire magnets being fabricated from this material.

Batteries

Although lead-acid batteries are a commercial product, and have been for many years, battery energy storage systems are still new. There are still issues of balancing strings, watering, venting, trickle charging and thermal control, all of which effect cycle and shelf life. Replacement time is a major issue for batteries. Advanced battery types, especially Zn/Br, are entering the power quality market also. These are especially attractive because there are no toxic materials or disposal issues. Designs are now becoming standard and manufacturing volume should result in lower costs.

Fuel Cells

Fuel cells are perhaps the least mature of all the technologies considered in this study. At least they are the farthest in cost from their target. PEM fuel cells, especially, are immature; platinum loadings are high and need to be minimized or replaced with an alternative material. Dynamic response fuel cells have been demonstrated, but need to be scaled up in size for ultimate usefulness. Even the auxiliary components need development, i.e., the hydrogen storage technologies and fuel processing systems.

When efficient and standard components are available this should reduce the cost to a point from which manufacturing in volume production can reduce the costs further.

B

APPENDIX: GENERIC CHECKLIST DESCRIBING ESSENTIAL SPECIFICATION & INSTALLATION ISSUES

Defining and Selecting PQ Mitigation Equipment

Output Power Characteristics

Power rating: ___kva.
Steady-state voltage: ___V RMS.
Voltage transient and recovery: +___%, -___%, ___second.
Frequency limits: ___Hz, ± ___Hz.
Line-to-line voltage unbalance: ___%.
Load unbalance ratio: ___:1.
Voltage modulation: ___%.
Waveform deviation factor: ___%.
Total harmonic content: ___% RMS.
Phase angle: ± ___°.
Overload: ___%, ___ seconds.
High momentary loads: ___amperes, __-second.
Current limit.
External fault clearing.
Internal fault clearing.

Response Time Required

Milliseconds _______
Cycles ______

Ride-through Time Required at Full Load

Seconds ______
Cycles _______

Storage Medium Required (from no load to full load)

DC Voltage Range____to____
AC Voltage Level____to_____
Maximum Discharge Rate______
Maximum Charge Rate______

Other Requirements

Audio noise level.
Growth provision to: ___kva.
Automatic bypass operation.
EMC.
Input voltage harmonics: ___% RMS.
Efficiency.
Reliability and maintainability.
___MTBF: _____ hours.
___MTTR: ___-hours.
Safety.

Determining Power Rating

Present system load: ___kva.
Planned additions: ___kva.
Long-range expansion: ___kva.
Critical lighting: ___kva.
Other critical loads: ___kva.

Optional Features

Remote console.
Emergency power-off interconnection.
Special EMC requirements.
Lighting and cooling during outage.
Nonstandard input power voltages.
Special acoustic or aesthetic requirements.
Automatic start of and transfer to E-G.
Smoke detectors.
Additional spare parts and test equipment.

Site Selection

Temperature: ___°C to ___°C (___°F to ___°F).
Relative humidity: ___% to ___%.
Altitude: ___meters (___ feet)
Ventilation and/or air conditioning.
Acoustics.
Safety.
Floor loading.
Space.
Accessibility.
Growth.
Lightning protection.
Earthquake conditions.

Power Distribution

Single-line electrical diagram.
Input power source impedance.
Connection diagram.
Independent mains bypass feeder.
Circuit Protection.
_____ Input .
_____ load.
_____ Energy Storage Device
_____ Input to load (bypass).

Requests for Proposals

Parameters and information in first four sections.
Reliability.
_____ Average utility failure rate: ____
_____ Average utility failure duration: _______
Maintenance.
_____ Strategy 1 (all supplier provided) or
_____ Strategy 2 (all user-provided) or
_____ Strategy 3 (parts of 1 and 2).
_____ Time between notification and arrival of service personnel: _____________.
_____ Training.
_____ Maintenance documentation.
Operator training.
Single-point failures.
System ground constraints.
Warranties.
Electrical codes.
Structural codes.
Safety codes.
Contracts.
Schedules.
Input power.
_____ Maximum: _____kva.
_____ Power factor: ___.
_____ Voltage harmonics: ___% RMS.
Energy Storage
_____ Voltages.
_____ Float: _____V.
_____ Equalization: _____ V.
_____ End: _____ V.
_____ Rated dc current at full load: _____ amperes.
_____ Maximum available dc short-circuit current: _____ amperes.
_____ Ride-through time at full load..
_____ Projected life: ___ years
_____ Operating temperature ___°C, ± ___°C (___°F, ± ___°F).

Proposed Evaluation

Compliance statements.
Deviation statements.
Visits.

Acceptance Tests

Output voltage regulation.
Bypass switch.
PQ mitigation performance
Environment.
Instrumentation, controls, and indicators.

Installation

Compliance with codes, regulations, drawings, and specifications.

Total System Acceptance Tests

Dummy load tests.
_____ Output voltage regulation.
_____ Energy Storage.
_____ Static bypass switch.
_____ Instrumentation, controls, and indicators.
_____ System grounds.
_____ Serviceability.
Live load tests.
_____ Output voltage regulation.
_____ Static bypass switch.
_____ Long-term run.
_____ Safety.

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