Power Quality Solutions and their Costs

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Abstract This presentation relates to electric power quality, with emphasis on contemporary issues, cost / benefit, and the present technology of the field. Covered are:

- *Classes of power quality problems and their solutions*
- *Costs of events and solutions*.

Keywords Power quality; power distribution engineering; dynamic voltage restorer; voltage sags , cost to benefit ratio, CBEMA curve .

I. INTRODUCTION

POWER quality engineering has always been an integral part of power engineering in general. However, in recent years, the impact of electronic loads has motivated attention to the impact of these loads on the power system (and other loads), and the impact of the system on local electronic loads. In this paper, two issues are discussed in some detail:

•*Classes of power quality problems and their solutions*

In this area, the classification of power quality problems is considered, with emphasis on international standards and methods of classifying primary and secondary distribution problems by duration, type, and severity. The IEEE classes shall be discussed in detail. Harmonics in power systems shall be discussed. Momentary events have received considerable attention in contemporary power engineering, and the details of momentary outages and sags shall be described. Momentary events such as distribution voltage sags have been the highest profile power quality problems in recent years. Solutions for residential, commercial, and industrial applications are considered.

•*Costs of events and solutions*

Cost is a driving influence in most branches of engineering, but the subject has dominated power engineering in recent years. Cost is especially important in distribution engineering because of the geographical extent of power distribution systems and the investment in equipment in this sector. The cost / benefit of power quality solutions shall be discussed, and this shall include technologies such as the dynamic voltage restorer, static var compensator, transient voltage regulator, sub-cycle transfer switch, and transient surge suppressor. Recurring costs may be attributed to many power quality problems including: conductor losses, equipment loss of life; increased peak demand; and disruption of customer processes (especially computer controlled loads).

The paper shall include some recent results on the control of electronic power quality enhancement devices. In this area, the advantages of phasor control versus mathematical techniques in both the time and transformed domains shall be contrasted. Included in considerations of power quality enhancement are design considerations of static capacitor placement. A listing of power quality controllers and equipment appears in Table I. Some generalized conclusions, particularly remarks addressed to distribution engineers, shall be drawn from the foregoing.

TABLE I POWER QUALITY ENHANCEMENT EQUIPMENT

		Typical voltage (kV)	*Typical power (energy)*
CVT	Constant voltage transformer	0.11 – 1	0.25 – 300 kVA
DVR	Dynamic voltage restorer	13.8 – 35	10 – 40 MVA
MOV	Metal oxide varistor	All voltages	All power levels
	Passive filter	All voltages	All power levels
	Power Conditioner	0.11 –13.8	0.001 – 1.0 MVA
SCTS	Subcycle transfer switch	13.8 – 35	10 – 40 MVA
SMES	Superconducting magnetic energy storage	13.8 – 35	10 – 40 MVA (to 20 MJ)
SVC	Static var compensator	13.8 – 35	1 – 40 MVA
TVR	Transient voltage regulator	0.22 – 35	10 – 40 MVA
TVSS	Transient voltage surge suppressor	All voltages	All power levels
UPS	Uninterruptible power supply	0.11 –13.8	0.001 – 1.0 MVA

II. CLASSES OF POWER QUALITY PROBLEMS

Power quality problems are generally classed into recurring phenomena such as harmonics and non-recurring events such as momentary sags. In this paper, the non-recurring phenomena are the focus of interest. The IEEE Standard 1159 [1] gives the categories and typical characteristics of non-recurring power system events. Table II shows the terminology of IEEE 1159 and the classification of events by duration of event. The actual standard represents some of these duration times in ‘cycles’.

TABLE II
DURATION OF SHORT-TERM VOLTAGE VARIATIONS USING IEEE 1159 (DURATIONS SHOWN IN MILLISECONDS FOR A 60 HZ SYSTEM)

	Category of short duration variation		
Type of variation	Instantaneous	Momentary	Temporary
Interruption (ms)		8.33 – 3000	3000-60000
Sag (ms)	8.33 – 500	500 - 3000	3000-60000
Swell (ms)	8.33 – 500	500 - 3000	3000-60000

Table III shows the typical severity of events represented as voltage magnitudes. European norms require voltage sags (dips) [2] to be entered in a spreadsheet organized as depth of sag versus duration. The European norm uses sag depths [10, 30), [30, 60) and [60,100) percent; and durations [10, 100 ms), [100, 500 ms), [500, 1000 ms), [1, 3 s), [3, 20 s), and [20, 60 s). Fig. 1 shows the time scale of various voltage disturbance events using the terminology of IEEE 1159.

TABLE III
TYPICAL VOLTAGE MAGNITUDE FOR SHORT DURATION VARIATIONS OF LOW AND HIGH VOLTAGE EVENTS IN POWER DISTRIBUTION SYSTEMS (IN PER UNIT)

	Category of short duration variation		
Type of variation	Instantaneous	Momentary	Temporary
Interruption (pu)		< 0.1	< 0.1
Sag (pu)	0.1 to 0.9	0.1 to 0.9	0.1 to 0.9
Swell (pu)	1.1 to 1.8	1.1 to 1.4	1.1 to 1.2

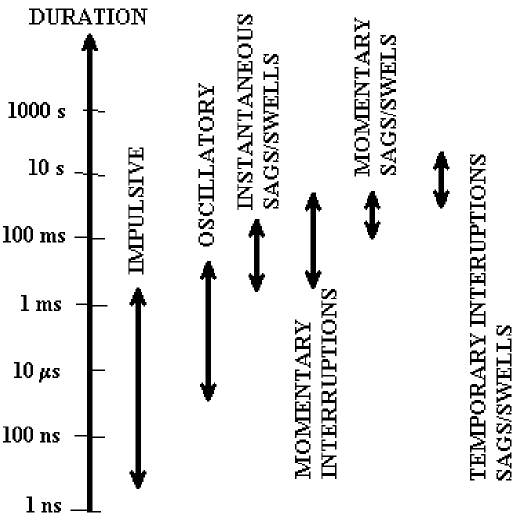

Fig. 1 Categories of voltage disturbance events according to event duration using the terminology of IEEE 1159

It is possible to integrate the usual CBEMA curve (or alternative CBEMA-like curves, for specific load types) with IEEE 1159 definitions of voltage sag. The same procedure can be applied for a non-differentiate representation of load sensitivity to voltage sags, as in [3], but, when discrimination among disturbances are available only in terms of IEEE 1159, the method proposed here becomes easier to handle. This is illustrated using the conventional CBEMA curve in Fig. 2 .

Long duration undervoltages are depicted at the far right in Fig. 2 as sustained events (e.g., steady state). Instantaneous, momentary, and temporary sags are shown below the CBEMA curve in the appropriate time interval. Three IEEE Standards, namely IEEE 1159, IEEE 1250, and IEEE 859 are indicated in Fig. 5 with their approximate range of scope in duration of disturbances [1,2,4,5].

There are a range of electronic solutions to power quality problems, and most share the following attributes:

- Electronic controls are fast – that is, in the subcycle range, they are able to correct problems as they occur. It is generally accepted that sensing and correction can be accomplished in the half cycle time range.

- Electronic controls often are expensive – and this requires designs such that sensitive loads are afforded the specialized equipment, and unnecessary loading of the equipment is avoided.

- Controls must be designed with speed in mind for certain loads, and with accuracy of response in mind in some cases.

- Usually a pulse width modulation technology is utilized in these devices for controllers that require a controlled AC waveform synthesis.

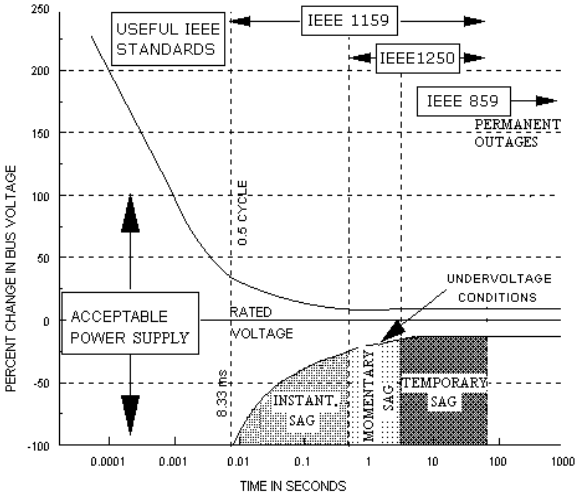

Fig. 2 IEEE 1159 sag durations integrated with the CBEMA curve

III. SOME ELECTRONIC SOLUTIONS TO POWER QUALITY PROBLEMS

Table IV shows some of the electronic power quality enhancement devices and a concise description of certain properties

TABLE IV THREE TYPES OF ELECTRONIC POWER QUALITY ENHANCEMENT DEVICES

	Dynamic voltage restorer	*Subcycle transfer switch*	*Dynamic voltage regulator*
Requires AC wave synthesis	**X**		
Employs energy storage	**X**		
Requires multiple feeds		**X**	
Effective mainly for isolated infrequent events		**X**	**X**
Cost	Highest	Lowest	Lower
Response to sags is smooth	**X**		

The dynamic voltage restorer (DVR) employs series voltage boost technology using solid state switches to correct the load voltage amplitude as needed. The basic concept is that during sag, a voltage is electronically developed in the DVR using pulse width modulation (PWM) technology that has controlled phase and amplitude. This developed controllable voltage is added to the supply voltage through the use of a series transformer (see Fig. 3). The resultant of this addition is the required load voltage (see Fig. 4). Reference [6] describes DVR operation and design, and [7], [8] give some operational experience. It is estimated that there are about 30 DVRs in the 10 - 40 MVA class are in operation worldwide. Smaller units down to the secondary distribution voltages are also commercially available. The main application is in distribution bus voltage regulation for very sensitive loads.

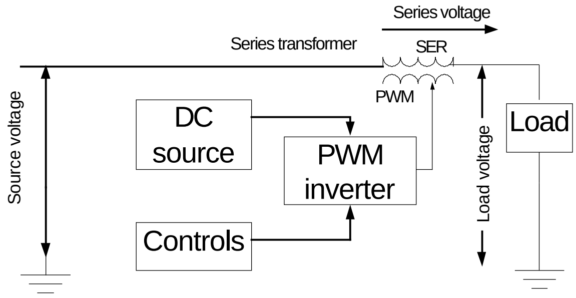

Fig. 3 Conceptual diagram of a DVR

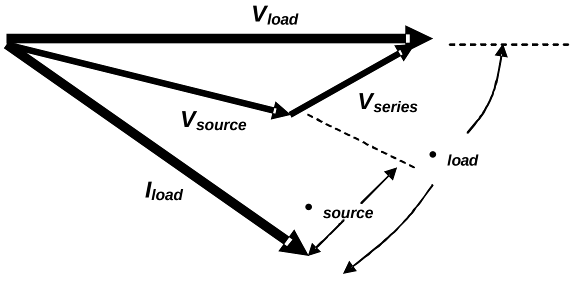

Fig. 4 Basic DVR phasor diagram, power factor angles at the source and load side of the DVR shown

As an example of the effectiveness of a DVR, Figures 5 and 6 are offered. These traces are supply side voltage and load side voltage of a functioning DVR [16]. For the depicted application, 69 kV subtransmission voltage is stepped down at a substation at which a DVR is sited. The primary distribution voltage is 12.47 kV. The figures depict a voltage sag in the supply. This is a 60 Hz application at a sensitive load.

Fig. 5 Supply side voltage waveform obtained from the DVR installation (vertical scale in instantaneous volts line to neutral, horizontal scale in recorded data points)

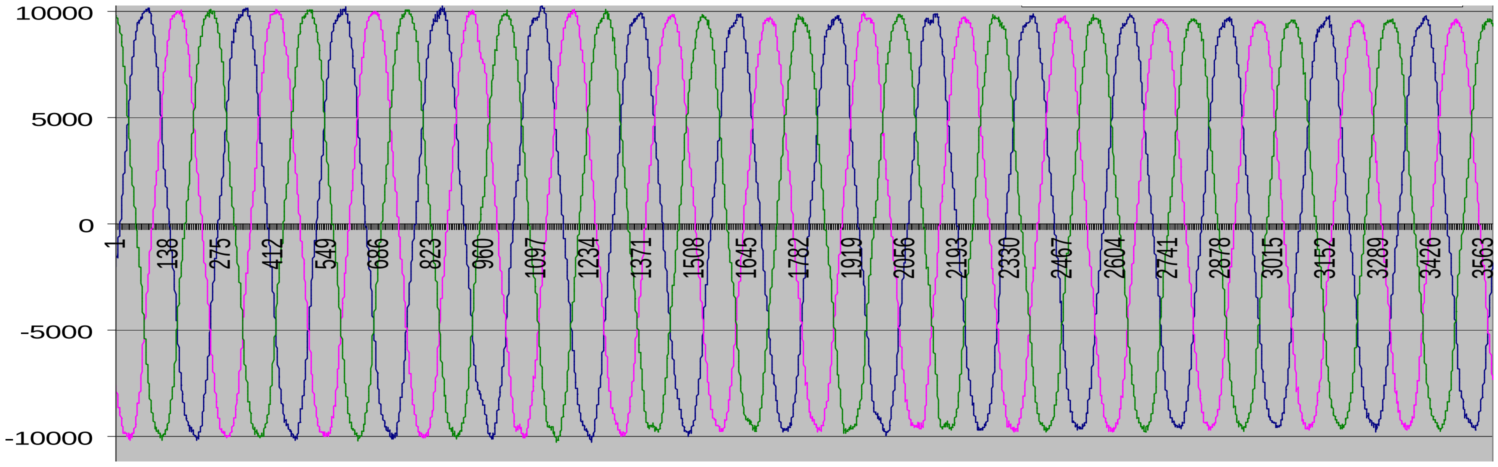

Fig. 6 Corrected load side voltage waveform obtained from the DVR installation (vertical scale in instantaneous volts line to neutral, horizontal scale in recorded data points)

A transient voltage regulator (TVR) is essentially an electronically switched tapped transformer. The TVR usually utilizes a tapped autotransformer. This device requires multiple bilateral AC switches to allow tap changing. The tap changing is discrete, and therefore the load voltage during corrections may not be smooth. The TVR generally requires many full rating AC electronic switches. Control of a TVR is usually relatively simple, and based on voltage regulation of the load bus. Fig. 7 is a depiction of the TVR.

The subcycle transfer switch is depicted in Fig. 8. The concept is that two independently derived feeders are switched to afford the 'best' supply to the load. There is no energy storage in this device, and there is a clear disadvantage of needing two independently derived feeders.

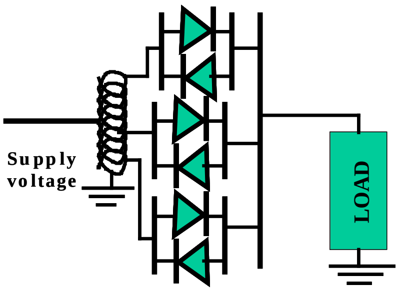

Fig. 7 Transient voltage regulator

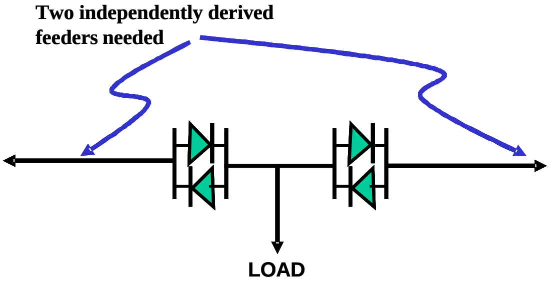

Fig. 8 Subcycle transfer switch

IV. COMMENTS ON CONTROL STRATEGIES

The control of power quality enhancement equipment can be somewhat tricky since the controls must respond to transients in such a way as to render the load voltage nearly fixed in amplitude, and yet noise and feedback effects should not disrupt the controls. In particular, it is common to reduce the bandwidth of system disturbances and eliminate the power frequency variation by some means. One concept is to work with root-mean-square values – but the disadvantage here is that rms values require at least one cycle for calculation. The main motivation of electronic controls is the high speed (e.g., sub-cycle). One alternative control procedure that seems to be popular in several applications is the use of the *dq0* transformation to avoid the direct processing of three phase variables (i.e., $v_a(t)$, $v_b(t)$, $v_c(t)$). Control using the dq0 transformation also avoids the processing delay inherent in working with root mean square phasor values. The *dq0* transformation is

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & 1 \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

where the phase and transformed voltages are shown, and • is selected on the basis of a reference phasor (usually the *a*-phase (red-phase) supply line-neutral voltage and the power flow in the DVR). Note that

$$\theta = \omega_r t + \theta_o$$

where $\bullet_r$ refers to the power frequency, and $\bullet_o$ can be nominally chosen as zero in this application. Since (1) is a purely real transformation, there is no assumption of sinusoidal steady state (as needed in phasor controls). The use of the *dq0* transformation is very similar to Clarke's •, •, *0* transformation, and both transformations yield a low bandwidth signal that effectively decouples the modes of the electrical supply. The latter is evident by inspection of (1) and noting that the frequency spectrum of the transformed variables contains 'sum and difference' frequencies of the transformation matrix itself and the untransformed, phase variables. The advantage of working with a smaller bandwidth signal as a control signal is that response time can be faster.

Reference [17] discusses the *dq0* transformation, and [18] describes the properties of another real transformation, Clarke's transformation. It appears, from conversations with power conditioning equipment manufacturers, that there is no 'standard' way to accomplish power conditioning. Controls of many configurations working in several transform domains are possible.

V. COSTS OF POWER QUALITY EVENTS

The subject of cost of power quality degradation is fraught with many pitfalls and controversy. Among these difficulties are:

- Should cost of power quality degradation be calculated on the basis of the cost of interrupted industrial processes? And if so, is the final product cost used as the cost of the interruption – or is the cost of the raw material used as the cost?

- Should the cost of power quality enhancement equipment be used as the cost of power quality?

- In many cases, engineering and training might be attributed to power quality awareness. Should these elements be calculated in the cost of power quality?

- Should lapses in power quality include such recurring phenomena as the cost of harmonic currents in transformers (i.e., the kilowatt hour cost of core losses at harmonic frequencies)?

- Some estimates of interruptions are based on 'event count indices'. These indices include the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and the System Average RMS (Variation) Frequency Index Voltage Threshold (SARFI).

- The cited event count indices are defined as:

SAIFI = (Total number of interruptions) / (Total number of points of delivery monitored).
SAIDI = (Total duration of all interruptions) / (Total number of points of delivery monitored).
SARFI%V = (Summation of the number of customers experiencing rms < %V for variation k (rms > %V for %V >100)) / (Total number of customers).

For the above indices, only temporary interruptions are to be counted.

- In order to quantify voltage sags, subsets of SARFI%V are used, defining indices according to IEEE 1159:

SIARFI%V = (Summation of the number of customers experiencing rms < %V for instantaneous variation k (rms > %V for %V >100)) / (Total number of customers).
SMARFI%V = (Summation of the number of customers experiencing rms < %V for momentary, i.e. 30 cycles to 3 seconds, variation k (rms > %V for %V >100)) / (Total number of customers).
STARFI%V = (Summation of the number of customers experiencing rms < %V for temporary, i.e. 3 to 60 seconds, variation k (rms > %V for %V >100)) / (Total number of customers).

Event-count indices have the advantage of ease in instrumentation and convenient comparison. Some electric utility companies set power quality targets on the basis of event-count indices. However, event-count power quality indices can not be translated easily (or accurately) into loss of load data. The most elusive of questions, namely the cost of power quality, is poorly depicted by event-count indices. It seems that tailored CBEMA-like curves, generated for specific load types and specific load dynamics, have a potential of capturing load response and load survival. Cost of events, also, can be estimated albeit the estimates of cost are only as accurate as the data used for the cost of a typical power quality disturbance.

Given these potentials for inaccuracy, there are some estimates of power quality costs available in the open literature. Unfortunately, many of these estimates come from one part of the world, and it may be necessary to extrapolate to attain worldwide costs. These estimates include:

- Clemmensen's estimate of $33*10^6$ Australian \$ per year (\$AU/y) for interruptions in the United States for the manufacturing sector [9].
- Swaminathan and Sen's estimate of $192*10^6$ \$AU/y of interruptions of all types in industrial power systems in the United States [9].
- Primen's estimate of $152*10^6$ \$AU/y for commercial and industrial interruptions in the United States [9]. The Primen study categorizes costs into $133*10^6$ to $210*10^6$ \$AU/y for power outages, and $19*10^6$ to $31*10^6$ \$AU/y for 'power quality' lapses.
- Heydt's estimate of $4*10^6$ \$AU/y attributable to harmonic losses in distribution transformers in the United States [10].
- McEachern's estimate of $64*10^6$ \$AU/y for all power quality problems in the United States – anecdotally in 1996.
- A Canadian estimate of cost of power quality degradation on a per kilowatt basis (see Table V) [11].
- Various 'fuzzy' estimates of costs of interruptions, mainly in North America [12, 13]. And a newspaper article mentioning $101*10^6$ \$AU/y for loses due to interruptions of industrial processes in the US [14].

TABLE V
AVERAGE COST OF POWER INTERRUPTION – FROM A CANADIAN SURVEY [11]

IEEE 1159 class	*Average cost* ($AU / kW)
Instantaneous	0.100
Momentary	0.225
Temporary	1.56
Sustained	4.65

World figures could well be ten times the quoted U. S. costs, and the author estimates that Australian figures are in the range of 5.5 % of US costs. The latter conjecture is based simply on the ratio of the generated MWh in Australia to that in the US (2003 data). No matter how the estimates are calculated, the figures are staggering, and they suggest that amelioration measures are justified well into the range of over 128 $AU per kilowatt of served load. Obviously, the more sensitive the load (e.g., computer controlled loads of uninterruptible processes), the higher this figure is justified. A presently often quoted figure of 320 $AU per kilowatt is given for power electronic devices of the type that may offer solutions to power quality problems.

VI. A DISCUSSION OF COST TO BENEFIT RATIO

The cost figures cited above represent a wide range of dollar figures. The data in Table V might be used to assess the effectiveness of power quality enhancement equipment. For example, if the sustained events entail a cost of 4.65 $AU per kW of load interrupted, and costs of 100 $AU are expended per kW to solve those problems, the ratio of these numbers, about 21.5, is an index of how much the customer is willing to solve sustained interruptions. The data shown in Table V are national averages across Canada for all loads. In some industries, there are very sensitive computer controlled loads that are involved in the manufacture of high cost items – such as in the semiconductor fabrication industry. A widely quoted figure in the United States is for a loss of over $128*10^6$ $AU for a momentary interruption. The momentary interruption can result in the loss of product for a large volume of high value components (e.g., microprocessors). Also, restarting may be problematic. Figure 9 is an attempt to quantify and depict the cost / benefit ratio of electronic power quality enhancements. It appears that the confounding factors include:

- A difference of opinion among the manufacturers and the utilities as to the loss in dollars due to a momentary voltage sag
- The number of low voltage events per year (e.g., SAIFI)
- Residence of the responsibility for the highest possible quality of power delivery.

At lower power levels (e.g., in secondary distribution systems, in the 10 kW range and less), the cost to benefit ratio is far more favorable to solving power quality problems by electronic means: the electronic device costs are about one order of magnitude lower at the 110 – 220 V range (e.g., about 32 $AU/kW).

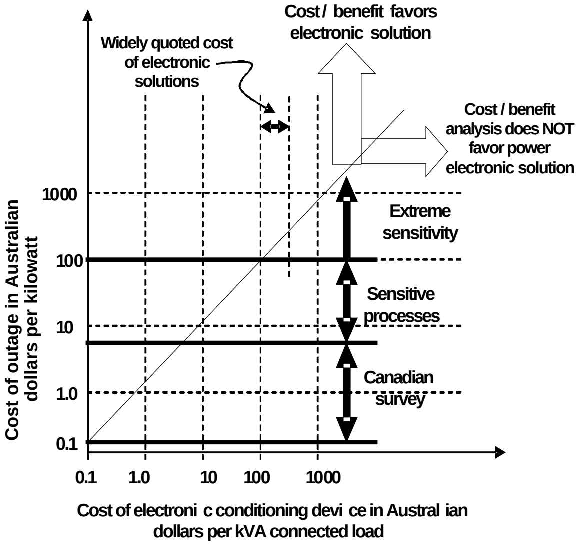

Fig. 9 A depiction of the cost to benefit ratio of power electronic solutions to electric power quality problems, based on data from a nationwide Canadian survey, and conjectures of power electronic costs.

Of course, passive devices (filters, transient voltage surge suppressors, metal oxide varistors) give a very favorable cost to benefit ratio, and these devices are in common use worldwide. Passive filters also have the favorable quality of providing reactive power support at the power frequency – but useful harmonic filtering at harmonic frequencies. This issue is discussed in detail in [15].

VII. CONCLUSIONS

The main conclusion of the paper is that power quality is an expensive feature of power delivery. There is an array of passive and active (electronic) power quality enhancement devices. The main high power electronic devices are the dynamic voltage restorer, the transient voltage regulator, and the subcycle transfer switch. These devices operate in the subcycle time range, and they are effective for solving many power quality problems. In particular, the DVR is effective for solving voltage sags. The control of a DVR has been discussed in terms of the *dq0* transformation. The *dq0* transformation offers the possibility of real time control because this transformation reduces the bandwidth of the bus voltages to be controlled.

The costs for active power quality conditioning devices are difficult to identify firmly. However, the 100 \$AU/kW range is quoted near the low end of the cost spectrum. The costs of power quality problems in the USA and Australia are speculated to be about $150*10^6$ \$AU/y and $8.3*10^6$ \$AU/y respectively. At least for the time being, it is concluded that electronic power conditioning is mainly relegated to the most sensitive, high production cost manufacturing processes.

VIII. ACKNOWLEDGEMENTS

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IX. REFERENCES

[1] IEEE Standard 1159-1995, "IEEE Recommended Practice for Monitoring Electric Power Quality," Piscataway, NJ, November 1995.

[2] A. Robert, "Power quality monitoring at the interface between transmission system and users," Proc. 2000 Harmonics and Quality of Power Conf., vol. 2, pp. 425-430.

[3] IEEE Standard 493-1997, "IEEE recommended practice for the design of reliable industrial and commercial power systems," Piscataway NJ, 16 December 1997.

[4] IEEE guide for service to equipment sensitive to momentary voltage disturbances, IEEE Standard 1250-1995, June 1995.

[5] IEEE Standard 859-1987, "IEEE standard terms for reporting and analyzing outage occurrences and outage states of electrical transmission facilities," Piscataway, NJ, February 1988.

[6] D. M. Vilathgamuwa, A. A. D. R. Perera, S. S. Choi, "Voltage sag compensation with energy optimized dynamic voltage restorer," IEEE Trans. Power Delivery, Vol. 18, No. 3 pp. 928-936, Jul 2003.

[7] J. G. Nielsen, F. Blaabjerg, "Comparison of system topologies for dynamic voltage restorers," Proc. 2001 IEEE Industry Applications Conf., Vol. 1, pp. 2397-2403.

[8] J. G. Nielsen, M. Newman, H. Nielsen, and F. Blaabjerg, "Control and testing of a dynamic voltage restorer (DVR) at medium voltage level," IEEE Trans. Power Electronics, Vol. 19, No. 3, pp. 806-813.

[9] K. LaCommare, J. Eto, "Understanding the cost of power interruptions to US electricity consumers," Lawrence Berkeley National Laboratory, LBNL-55718, September, 2004.

[10] G. T. Heydt, "The costs of impaired electric power quality," 1996 IEEE Transmission and Distribution Meeting, September 1996, Los Angeles, CA.

[11] G. Tollefson, R. Billinton, G. Wacker, E. Chan, J. Aweya, "A Canadian customer survey to assess power system reliability worth," IEEE Trans. on Power Systems, vol. 9, pp. 443-450, February 1994.

[12] M. J. Sullivan, T. Vardell, "Interruption cost, customer satisfaction and expectations for service reliability," IEEE Trans. on Power Systems, vol. 11, pp. 989-995, May 1996.

[13] K. Koellner, "SRP Voltage Index Methods and Findings," Proc. 2002 North American Power Symposium, pp. 239-246.

[14] A. Chen "Power interruptions cost US \$79 billion annually," Berkeley Lab View, Berkeley CA, January 21, 2005.

[15] G. Heydt, Electric Power Quality, Stars in a Circle Publications, Scottsdale, AZ, 1997.

[16] Siddharth Suryanarayanan, Gerald T. Heydt, Rajapandian Ayyanar, Rao S. Thallam, A. Barry Cummings, John D. Blevins, Scott W. Anderson, "Feed forward control of a dynamic voltage restorer," submitted for publication, IEEE Trans. on Power Delivery, 2005.

[17] P, Kundur, Power System Stability and Control, EPRI, Palo Alto CA, 1994.

[18] G. Heydt. Computer Analysis Methods for Power Systems, Stars in a Circle Publications, Scottsdale AZ, USA, 1996.

X. BIOGRAPHY

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