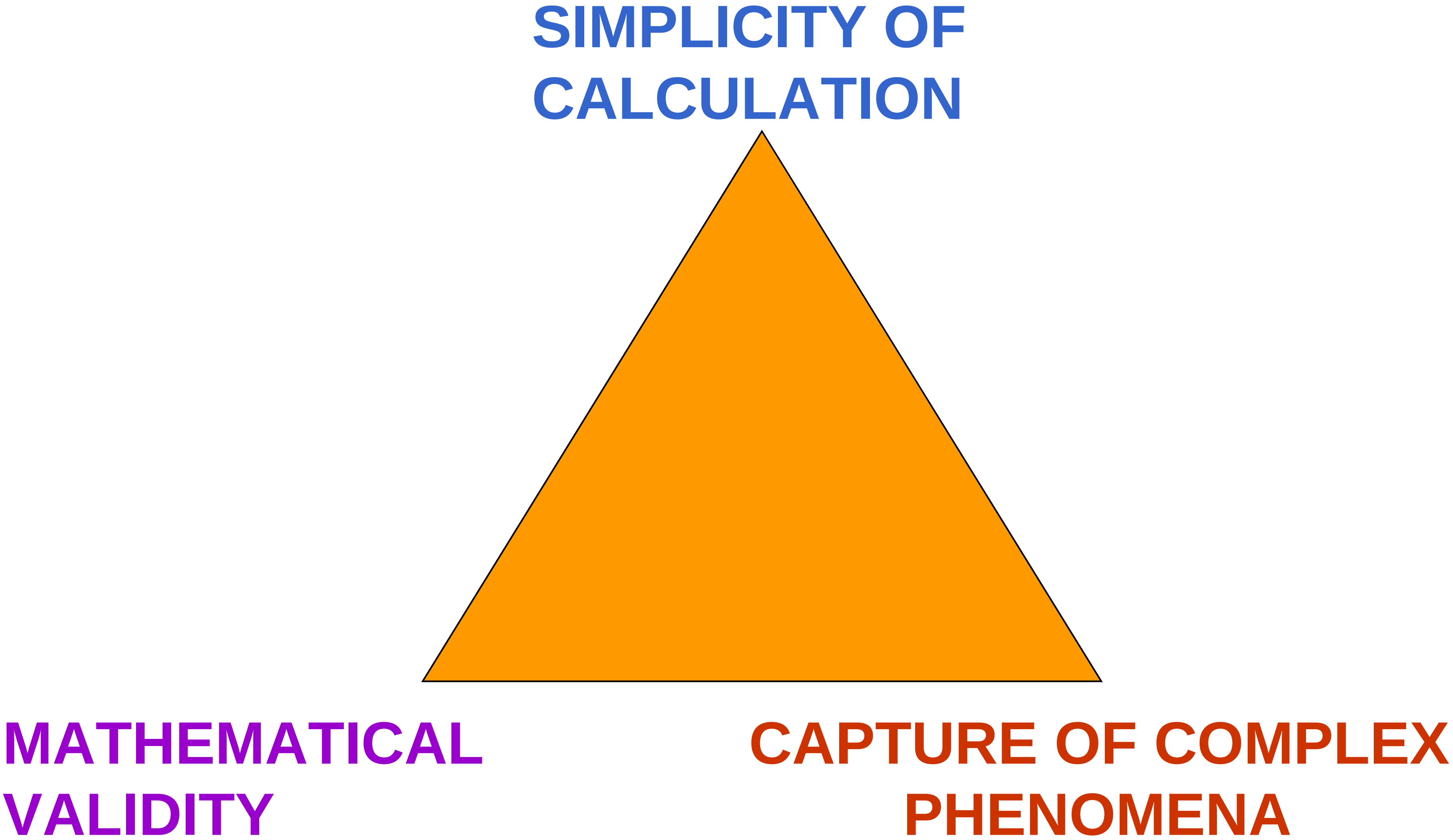
Power Acceptability and Voltage Sag Indices in the Three Phase Sense

R. S. Thallam
Salt River Project
Phoenix, AZ

G. T. Heydt
Arizona State University
Tempe, AZ

The electric power acceptability curves are an empirical set of curves that represent the intensity and duration of bus voltage disturbances. These curves are discussed with regard to the energy delivered to the load, and alternatives for the assessment and measurement of bus voltage sags. Special attention is given to the three phase case.

$$THD = \frac{\sqrt{\sum_{i=2}^{\infty} I_i^2}}{I_1}$$

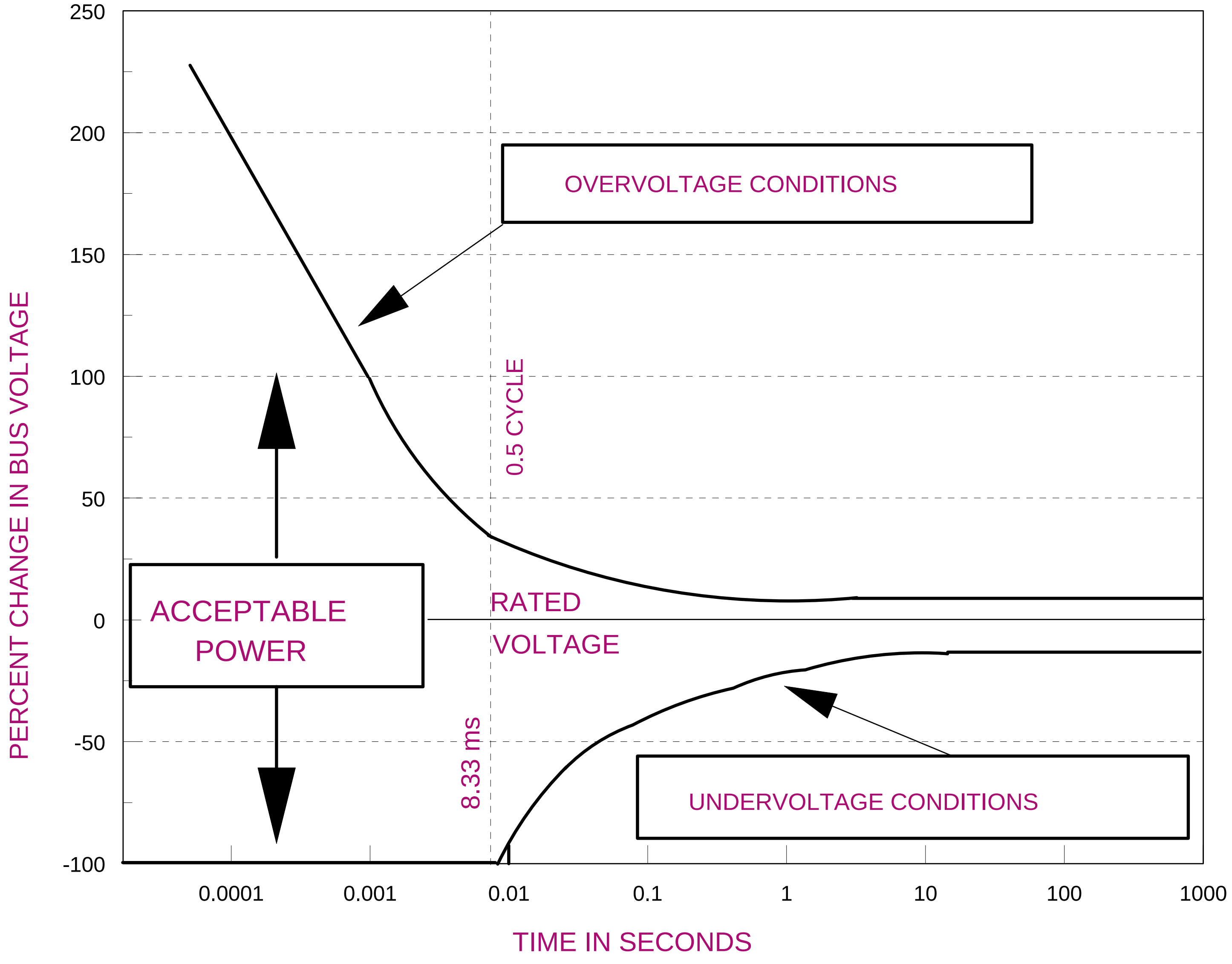


SIMPLICITY OF CALCULATION

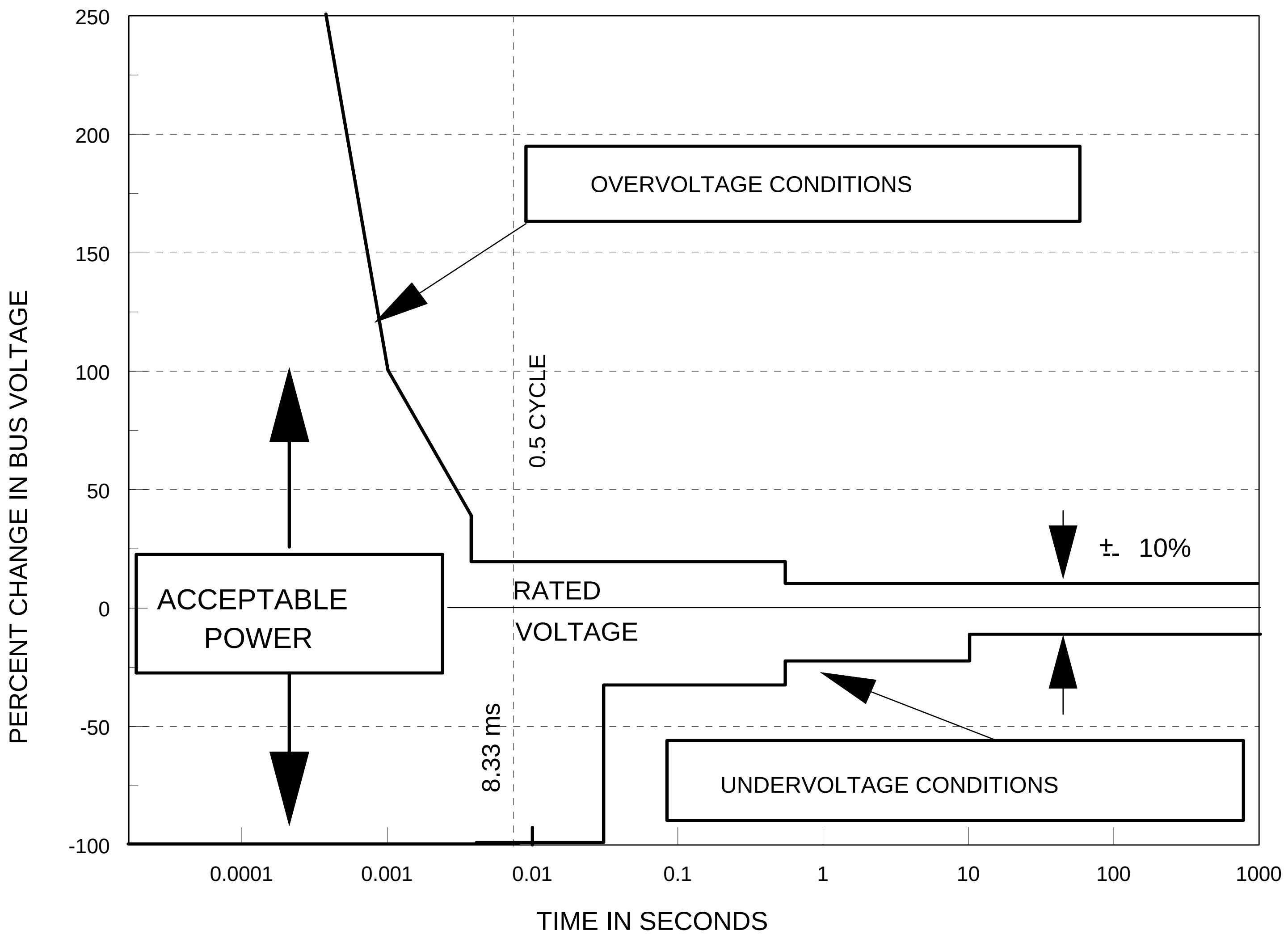
MATHEMATICAL VALIDITY

CAPTURE OF COMPLEX PHENOMENA

THE CBEMA CURVE



THE ITIC CURVE



Curve	*Year*	*Application*	*Source*
FIPS power acceptability curve	1978	Automatic data processing (ADP) equipment	U.S. federal government
CBEMA curve	1978	Computer business equipment	Computer Business Equipment Manufacturers Association
ITIC curve	1996	Information technology equipment	Information Technology Industry Council
Failure rate curves for industrial loads	1972	Industrial loads	IEEE Standard 493
AC line voltage tolerances	1974	Mainframe computers	IEEE Standard 446
IEEE Emerald Book	1992	Sensitive electronic equipment	IEEE Standard 1100

Factor	*Main difficulty*	*Potential problem*
Load dynamics	The load is a dynamic process, and a static curve may be unable to identify load vulnerability	The power acceptability curve may falsely dismiss a problematic power supply condition or may falsely identify an acceptable power supply condition
Three phase	The primary distribution system is usually three phase. The power acceptability curves seem to be single line (or single phase) representations.	Inability to identify cases of unbalance, excessive negative or zero sequence.
Short term phenomena – phase information	The power acceptability curves show Δ|V| versus time. But voltage disturbances depend on where in the cycle the disturbance occurs (for short duration disturbances). No phase information is plotted on the power acceptability curves.	It is expected that disturbances that occur near voltage zeroes will have less effect that those that occur near voltage peaks. But all disturbances are treated equally with respect to phase in the application of the power acceptability curves.

Factor	*Main difficulty*	*Potential problem*
Frequency	The power acceptability curves no not consider harmonics or deviations in supply frequency.	Deviations of frequency are not accounted.
Multiple events	Repeated disturbances (occurring near in time to each other) are not considered.	Events that are deemed 'acceptable' may not be acceptable if they are repeated close in time to each other.
Long term events	Are long term events the province of the power acceptability curves?	These events may be reliability issues.
Grounding	Neutral to ground voltage not modeled.	Neutral voltages may present a hazard and create unacceptable operating conditions. Similarly, neutral currents may be unacceptable.
Wrong energy model	The given power acceptability curve does not properly model the vulnerability of a selected load.	A single static power acceptability curve may not be able to model all load types.

Voltage Sag Index Using *Lost Energy*

An overvoltage or an undervoltage event at the load terminals will have impact, because either excess energy is delivered for an overvoltage event or some energy is not delivered to the load for an undervoltage event. The impact depends on how much excess energy is delivered or how much was *not* delivered. Many of the equipment installed in industrial, commercial and residential loads are sensitive to voltage sag events. During a voltage sag, the voltage is below normal for some period of time which reduces the power and energy delivered to load by the system.

The Detroit Edison sag score is probably the first used in a contract by an electric utility. The score is

$$\text{Sag Score} = 1 - \frac{VA + VB + VC}{3}$$

Voltage sag data are aggregated for 15 minute interval at each location. If one or two phases are greater than 1.0 per unit (because of neutral shift), they will be reset to 1.0 p.u. Sags will be qualified. A qualifying sag has at least one phase equal to or below 0.75 p.u. That is, the sags with minimum voltage above 0.75 per unit are not counted.

Lost energy in a sag event

The lost energy in a sag event is *W* calculated from

$$W = (1 - V_{pu})^{3.14} * t$$

where V_{pu} is the per unit voltage during the sag event and *t* is the sag duration

Example: Calculated energy values for some hypothetical voltage sags. Only one phase voltage is used in this example.

Voltage (per unit)	Time (milliseconds)	$1 - V_{pu}$	$(1 - V_{pu})^{3.14} * t$
0.8	66.7	0.2	0.43
0.6	50	0.4	2.81
0.5	41.7	0.5	4.73

Number of qualified voltage sags: 3

Average Voltage Sag Energy Index: 1/3 (0.43+2.81+4.73) = 2.32

For three-phase calculation, lost energy for all three phases will be added,

$$\text{Energy Lost} = (1 - V1_{pu})^{3.14} * t1 + (1 - V2_{pu})^{3.14} * t2 + (1 - V3_{pu})^{3.14} * t3$$

In most cases, t1, t2 and t3 are equal.

Duration (s)	V1 (per unit)	V2 (per unit)	V3 (per unit)	Energy lost (per unit*ms)
0.099	0.89	0.72	0.90	1.99
0.952	0.85	0.85	0.86	6.91
0.067	0.87	0.67	0.84	2.38
0.167	0.85	0.89	0.73	3.33
0.082	0.94	0.75	0.71	2.75
0.1	0.92	0.70	0.68	5.11
0.067	0.96	0.85	0.86	0.32
0.3	0.73	0.72	0.76	13.82
0.082	0.96	0.72	0.71	3.19
1.417	0.63	0.62	0.65	129.01
0.116	0.82	0.87	0.66	4.64
0.485	0.96	0.81	0.78	6.83
0.45	0.96	0.82	0.75	7.87
2.67	0.81	0.74	0.96	20.03
0.249	0.87	0.92	0.80	2.09
0.067	0.97	0.86	0.84	0.35
0.301	0.84	0.64	0.57	34.39
0.084	0.86	0.67	0.85	2.98
0.2	9.73	0.29	0.70	76.07
0.286	0.83	0.82	0.93	2.48
1.064	0.67	0.71	0.66	85.07
0.133	0.87	0.79	0.82	1.82
3.983	0.75	0.76	0.75	37.06
0.3	0.82	0.74	0.77	8.71
0.165	0.88	0.59	0.58	21.08
0.1	0.78	0.64	0.98	4.91
0.066	0.81	0.82	0.82	0.96
0.067	0.96	0.82	0.71	1.68
2.008	0.72	0.70	0.70	63.99
0.033	0.98	1.0	0.82	4.59
0.083	0.93	0.96	0.38	18.52
0.484	0.97	0.84	0.98	1.54
0.05	0.89	0.81	0.93	0.33
0.015	0.98	1.0	0.81	0.08

Total sag energy: 576.9

Number of sag events: 34

Average sag energy index: 16.97

Duration (s)	V1 (per unit)	V2 (per unit)	V3 (per unit)	Energy lost
0.117	0.88	0.88	0.74	2.00
0.115	0.84	0.85	0.86	0.90
0.434	0.76	0.75	0.75	16.08
0.083	0.97	0.85	0.80	0.75
0.100	0.77	0.84	0.79	2.05
0.083	0.95	0.77	0.70	2.72
0.033	0.85	0.98	0.84	0.19
0.099	0.97	0.70	0.60	7.83
0.10	0.68	0.49	0.57	21.93
0.067	0.97	0.86	0.84	0.35

Total sag energy: 54.8

Number of sag events: 10

Average sag energy index: 5.48

Duration (s)	V1 (per unit)	V2 (per unit)	V3 (per unit)	Energy lost (p.u.*s)
0.117	0.88	0.88	0.74	2.00
0.115	0.84	0.85	0.86	0.90
0.434	0.76	0.75	0.75	16.08
0.083	0.97	0.85	0.80	0.75
0.100	0.77	0.84	0.79	2.05
0.083	0.95	0.77	0.70	2.72
0.033	0.85	0.98	0.84	0.19
0.099	0.97	0.70	0.60	7.83
0.10	0.68	0.49	0.57	21.93
0.067	0.97	0.86	0.84	0.35

Total sag energy: 43.8
Number of sag events: 10
Average sag energy index: 4.38

Sub-station	Total sag energy	Number of events	Average voltage sag energy index
A	576.9	34	16.97
B - bay1	54.8	10	5.48
B - bay2	43.8	10	4.38

Voltage sag events are a serious concern to industrial and commercial customers, and there is a need to develop indices to indicate the severity of events at a location. The index should be based on sag magnitudes of all three phases, and time duration of the event. An index based on lost energy during sag events is developed. The energy lost during a voltage sag event is a function of missing voltage and the time duration of the sag event. The power of voltage to calculate energy lost is based on the CBEMA curve. This method based on lost energy is explained by applying it to data obtained from power quality monitors.

Indices reflect the severity of the voltage sags at each location. It is recommended that when power acceptability curves are used to assess the power supply quality, for cases of loads that are effectively AC to DC converters, that the positive sequence supply voltage be used. A method to calculate positive sequence component of voltage from the three-phase time domain data is being studied.

Conclusions

With regard to the power acceptability curves and an index of compliance with these curves, there is a tradeoff between complexity of calculation, mathematical / physical validity, and requirement to capture complex phenomena

The best known power acceptability curve is the CBEMA curve (and the ITIC curve) which is nearly a locus of constant disturbance energy

Conclusions

Problematic areas in the use of the PACs include neglect of harmonics in the voltage supply, no modeling of nearby repeated disturbances, ignoring problems relating to improper grounding, complex three phase effects, improper modeling of ‘disturbance energy’

Conclusions

There is a need to develop an index for voltage sag performance

It is proposed that the index be based on sag magnitudes in all three phases

An index based on lost energy is proposed

Energy lost is a function of ‘missing voltage’ and duration of the event

Conclusions

The functional relationship of energy and |V|, namely $|V|^k$, is proposed

The general philosophy of the method is explained and illustrated with data from PQ monitors