Site Variation and Prediction of Power Quality

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***Abstract*—We use EPRI's Distribution Power Quality project data to characterize and predict voltage sags and momentary interruptions based on site characteristics. The quality of sites is widely dispersed. Rural sites have many more sags and momentary interruptions than suburban and urban sites. The strongest indicators of voltage sags are 1) circuit exposure, 2) lightning, and 3) a term with transformer impedance and number of feeders. We develop a linear model for predicting sags and another for predicting momentary interruptions based on site characteristics. We also compare transmission-level power quality to distribution power quality.**

***Index Terms*—Power quality, voltage sags, interruptions, power distribution.**

I. Introduction

USING data from power quality studies, we examine the variation in power quality at different locations. Our goal is to provide insight on how much power quality varies by site, what circuit parameters cause the variation, and to find ways to predict quality at a site. We focus on the most common and most problem-causing power quality disturbances—voltage sags and momentary interruptions—using various SARFI power quality indices. SARFI is the System Average RMS Frequency Index [1]. Characteristics of the site help identify the major influences on SARFI and allow us to predict the level of power quality at a location. Among other uses, utilities can use a prediction of the quality at a given site to find good sites to locate sensitive customers, to determine if a site is under-performing based on the given infrastructure, or to quantify the risk of offering premium power services.

We base our analysis on EPRI's Distribution Power Quality (DPQ) project, which recorded voltage sags and momentary interruptions at a large number of utility distribution sites in the US [2-4]. Finished in 1995, the DPQ project collected data from 24 utility systems at 276 locations on 100 distribution system feeders over a 27-month period. Site and circuit descriptors help us analyze the causes for site variations. Some notable details about the monitoring and our analysis:

1) All measurements were on the distribution primary. Of course, most customers connect to the distribution secondary. Normally, this means that a customer's equipment sees more events below a given threshold. Also note that for three-phase customers, a delta-wye transformer distorts the secondary voltages relative to the primary voltages.

2) All data was measured at three-phase points on the distribution circuit (single-phase locations were not monitored).

3) We present all data based on the worst of the three phase-to-ground phases, which is conservative because most faults are single phase. Some three-phase equipment is less sensitive to single-phase sags than to three-phase sags, and single-phase equipment only sees sags occurring its phase.

4) We only used sites with at least 200 days of monitoring.

II. Site Power Quality Distributions

Table 1 shows cumulative numbers of voltage sags measured at sites during the DPQ study. Other sources have presented similar tables based on averages—we show the data based on the median and upper and lower quartiles to highlight the variation. One use of Table 1 is to estimate the number of times a year disturbances will affect a device—for example, if a device is sensitive to any event below a voltage of 50% of nominal for longer than 0.1 seconds, then Table 1 shows that at half of the sites in the US distribution system, the device misoperates more than 5.9 times per year.

As an indicator, the average misrepresents the *typical* site power quality. The median represents site data better, where by definition, 50% of sites have values higher than the median, and 50% have values lower. In a skewed distribution, the average is higher than the median. Poor sites and anomalies such as a severe storm skew the average upward. In the DPQ data, the average is 31 to 115% higher than the median depending on the quality indicator as shown in Table 2.

Power quality varies widely by site. Fig. 1 shows cumulative distributions of different power quality indices along with statistics and a fit to a log-normal distribution. The bottom row (SARFI 70, 50, and 10) gives the number of voltage sags below 70, 50, and 10%, which are most applicable for relays, contactors, and other devices that drop out quickly. SARFI_X considers only short-duration rms events, defined as ½ cycle to one minute [5]. The top row of Fig. 1 shows data similar to the bottom row but for criteria that disregards very short events (the ITI curve [6] disregards sags less than 0.02 seconds, and the SEMI curve [7] disregards sags less than 0.05 seconds). The indices that exclude short events are more appropriate for computer power supplies and other devices that ride through short-duration events. $\text{SARFI}_{10\ (>0.4s)}$ is for momentary interruptions greater than 0.4 seconds, which differentiates between deep sags and total loss of voltage due to operation of a breaker or recloser.

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TABLE 1.
ANNUAL NUMBER OF POWER QUALITY EVENTS (MEDIAN AND UPPER AND LOWER QUARTILES) FOR THE DPQ FEEDER SITES WITH A 60-SECOND WINDOW.

	Duration, seconds							
Voltage	0	0.02	0.05	0.1	0.2	0.5	1	2
0.9	32.8 57.5 104.8	30.8 49.0 95.1	24.4 35.3 65.6	13.6 22.7 38.7	7.6 13.2 24.0	3.3 7.3 14.2	1.4 3.2 8.9	0.7 2.1 5.3
0.8	16.4 31.6 54.1	14.8 26.0 50.1	12.1 20.9 37.9	8.1 15.0 25.1	4.9 9.6 16.9	2.4 5.3 11.0	0.9 2.7 7.5	0.5 1.8 4.5
0.7	10.1 20.5 33.8	8.6 18.8 32.7	8.1 15.3 27.6	5.8 11.3 18.8	4.0 7.8 13.5	1.8 4.5 9.3	0.9 2.5 7.0	0.5 1.8 4.5
0.5	4.7 9.7 19.2	4.5 9.0 17.4	4.2 7.7 14.3	3.5 5.9 11.2	2.3 5.0 9.6	1.4 3.3 7.7	0.8 2.2 5.7	0.5 1.6 3.9
0.3	2.1 4.8 12.8	1.8 4.5 11.0	1.6 4.2 9.5	1.4 3.6 8.6	1.1 3.5 8.3	0.8 2.8 6.6	0.5 1.6 5.1	0.0 1.1 3.4
0.1	0.9 3.2 8.3	0.9 2.9 7.8	0.8 2.8 7.8	0.8 2.7 7.8	0.7 2.7 7.8	0.5 2.2 6.1	0.3 1.6 4.9	0.0 1.0 3.3

A B C represent the lower quartile *A*, the median *B*, and the upper quartile *C* of the total number of events below the given magnitude and longer than the given duration (up to one minute).

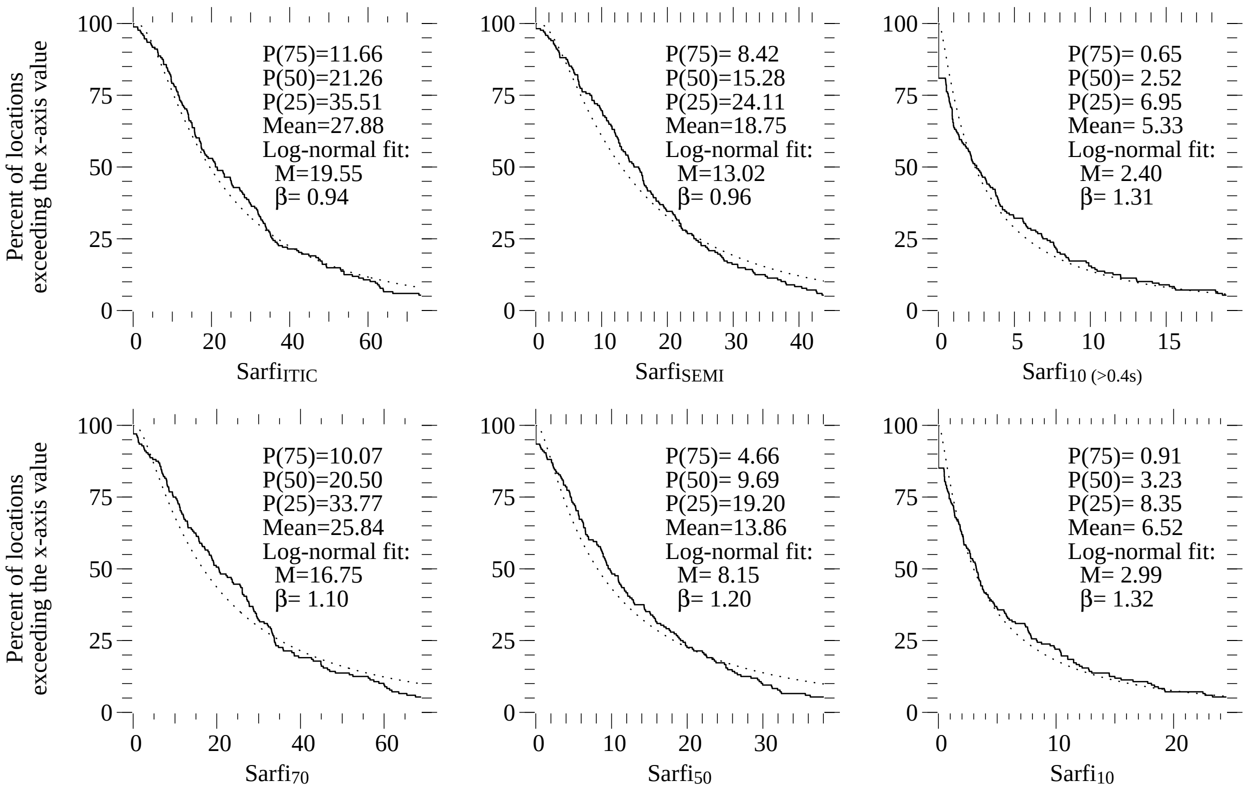

Fig. 1. Cumulative distributions of DPQ feeder sites along with statistics for various indices. SARFI 70, 50, and 10 gives the number of voltage sags below 70, 50, and 10%. $\text{SARFI}_{\text{ITIC}}$ and $\text{SARFI}_{\text{SEMI}}$ are events below the ITI curve and the SEMI curve respectively. The dotted line fits a log-normal distribution.

TABLE 2.
RATIO OF MEDIAN AND AVERAGE FOR DPQ SITE STATISTICS AT FEEDER SITES.

	Median	Average	Ratio of average to median
$\text{SARFI}_{\text{ITIC}}$	21.26	27.88	131%
$\text{SARFI}_{\text{SEMI}}$	15.28	18.75	123%
$\text{SARFI}_{10\ (>0.4\ \text{sec})}$	2.52	5.33	212%

The site data is not normally distributed. The site indices are nonnegative, and the distribution skews upward; therefore, we need another distribution, the log-normal, the Gamma, or the Weibull. Fig. 1 includes fits to log-normal distributions. The median (M) of the log-normal distribution equals the mean of the natural log of the values (x_i) raised to e: $M = e^{\text{mean}(\ln(x_i))}$. We can find β, the log standard deviation, with $\beta = \text{sd}(\ln(x_i))$.

A. Correlations Between PQ Indices

Fig. 2 shows the number of momentary interruptions at a site plotted against the number of voltage sags. We see that sites with high numbers of momentary interruptions probably also have high numbers of voltage sags. Sites with low numbers of momentary interruptions may have high or low numbers of voltage sags. The correlation coefficient between sags and momentaries for the DPQ sites is 44.8%.

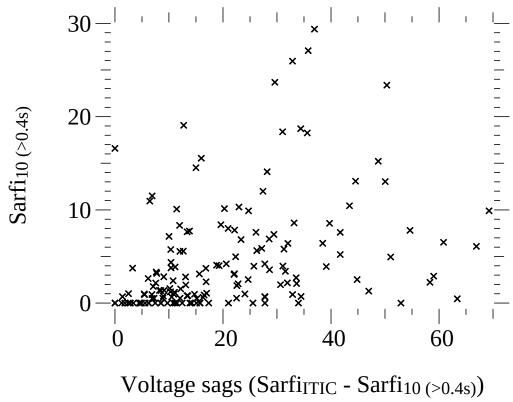

Fig. 2. Relationship between voltage sags and momentary interruptions (greater than 0.4 seconds). Each point gives the average voltage sags and momentary interruptions at a site (n=158).

Correlations between deep voltage and shallow sags are more pronounced. $SARFI_{90}$ and $SARFI_{50}$ have a 56.9% correlation coefficient. If we break the sites down by load density, the correlation coefficients improve to 90, 84, and 74% for urban, suburban, and rural sites.

B. Location

Three monitors were used on each circuit in the DPQ study. One was always at the substation, and two were on the feeder, named “feeder middle” and “feeder end.” The feeder sites were randomly picked on the circuits, so the naming is somewhat misleading; “feeder end” does not mean the most distant point from the substation (it just means the most distant of the two monitors randomly placed on the circuit). Since one third of the monitors are at the substation, the set is biased to “near-substation” customers since most customers are not located near the substation. Although there is some difference between measurement locations, it turns out that it is not drastic.

There is surprisingly little difference between the distributions of monitoring locations (see Fig. 3 for $SARFI_{ITIC}$). Fig. 4 shows a more specific comparison of the substation’s performance plotted against its two feeder sites. As expected, most feeder sites have more sags than their substation site, especially rural sites. A significant number of feeder sites were better than the substation, which are mostly due to measurement anomalies (eg. the substation recorder is down for part of a bad storm season)

For most of the analysis in this paper, we excluded substation sites, thinking that the feeder sites better represent a random feeder location where customers are fed.

C. Load Density

Rural sites have more voltage sags and momentary interruptions (see Table 3 and Fig. 5). This is not surprising given the extra lengths of line needed to serve load in low-density areas. Interruptions showed the most dramatic difference.

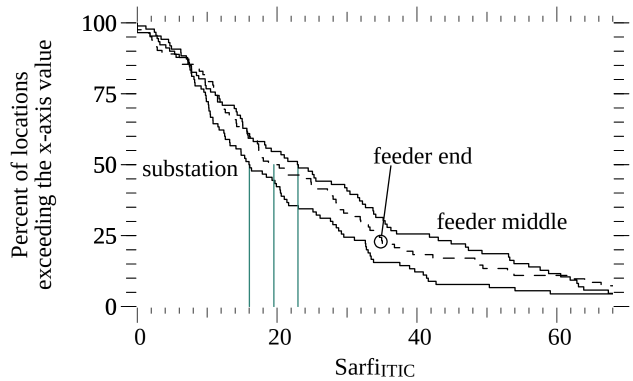

Fig. 3. Comparison of feeder sites and substation sites in the DPQ data for $SARFI_{ITIC}$.

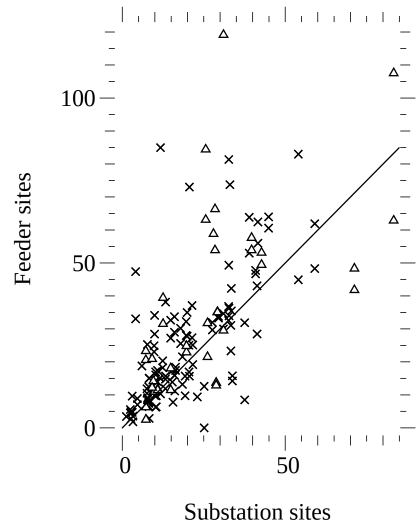

Fig. 4. $SARFI_{ITIC}$ at substation sites plotted against $SARFI_{ITIC}$ at that substation’s feeder sites (triangles indicate rural sites).

TABLE 3.
STATISTICS FOR MOMENTARY INTERRUPTIONS LONGER THAN 0.4 SECONDS.

	P(75%)	Median P(50%)	P(25%)
Rural	2.37	8.56	18.31
Suburban	0.23	2.39	6.71
Urban	0.00	1.37	2.82

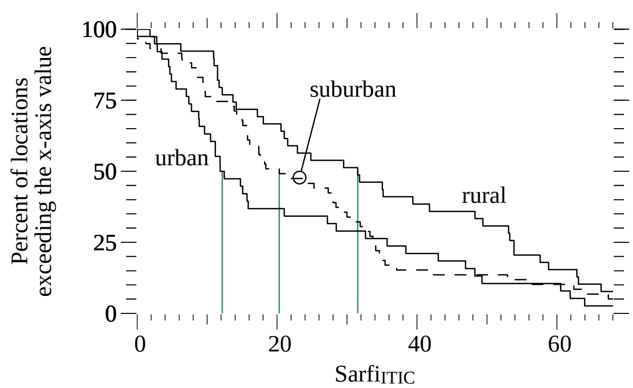

Fig. 5. Comparison of urban, suburban, and rural sites for $SARFI_{ITIC}$ (feeder sites only).

III. Site Characteristics Affecting Sags

Power system faults cause voltage sags and momentary interruptions. The frequency of faults depends on many factors including weather, tree-trimming and right-of-way maintenance, and age of equipment. The protection schemes and location of circuit interrupters determine whether a fault causes a voltage sag or an interruption, and the protection system determines the event duration.

We analyzed data available on the DPQ site characteristics to determine what parameters most affected power quality events. Fig. 6 shows the variations of $SARFI_{ITIC}$ with site characteristics.

The three most significant predictors of excursions below the lower ITI curve are:

1) Circuit exposure—The total circuit length including three-phase and single-phase portions is a good predictor of voltage sags. Any fault on the circuit sags the voltage.

2) Lightning—Lightning causes many faults on distribution systems, and lightning strongly correlates with voltage sags. In addition, lightning predicts weather patterns—areas with high lightning tend to have more storms and more wind and tree-related faults. We used the ten-year average (1988–98) from the US National Lightning Detection Network.

3) Station transformer impedance and number of feeders—The $n_f \cdot kV^2/MVA_{xfrmr}$ term in Fig. 6 contains the number of feeders off of the transformer bus along with an estimate of the transformer impedance.

This last term requires a bit more explanation. The following equation estimates the effect of feeder faults on voltage sags at the substation bus (this is a modification of the critical distances method in [8]):

$$S(V_{sag}) = n_f \lambda \frac{V_{sag}}{1 - V_{sag}} \left(\frac{Z_s}{Z_f} \right) \quad (1)$$

where,

S = annual number of sags per year where the voltage sags below V_{sag}

V_{sag} = per unit voltage sag level of interest (in the range of 0 to 1, e.g. 0.7)

n_f = number of feeders off of the bus

λ = feeder mains fault rate per kilometer per phase including faults on laterals and including both temporary and permanent faults

Z_f = feeder impedance in ohms/kilometer (usually use $(2Z_1+Z_0)/3$ for ground faults)

Z_s = source impedance in ohms

The number of bus sags is directly proportional to n_f, the number of feeders off the bus and to Z_S, the source impedance (a lower station transformer impedance, a bigger transformer or lower percent impedance, improves voltage sags at the station bus). The transformer impedance is $Z_{\%} kV^2/MVA$. We assumed the per-unit impedance of station transformers stays constant and just use kV^2/MVA. So, we have a term $n_f Z_S = n_f \cdot kV^2/MVA_{xfrmr}$ that should be a good predictor of sags.

These three main parameters had much more impact on sag frequencies than other parameters like tree coverage.

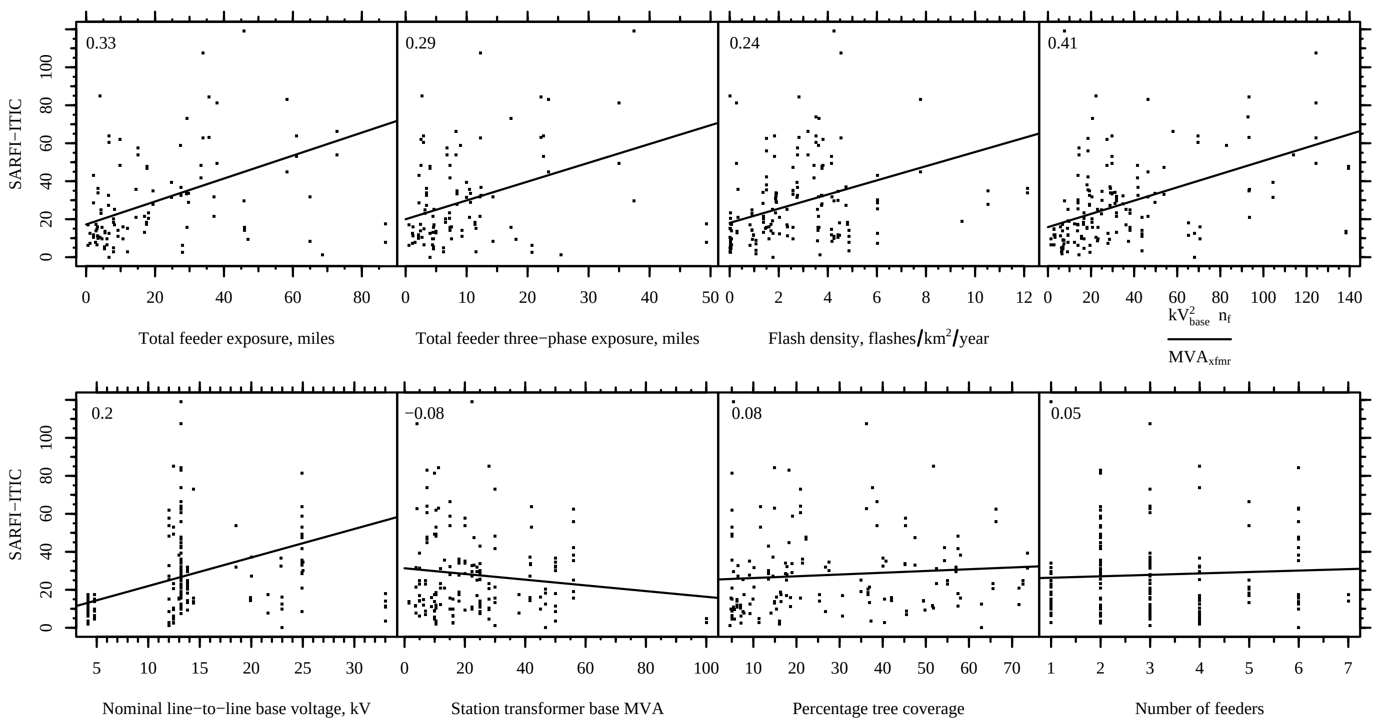

Fig. 6. Variations in the number of excursions below the lower ITI curve (which are mainly voltage sags) versus various site parameters. The correlation coefficients are given in the upper-left corner of each plot.

IV. Prediction of Quality Indicators Based on Site Characteristics

We derive a formula for predicting the number of events for a quality indicator based on a few of the characteristics of the site. If no measurement or historical data is available, this is useful in estimating the utility-side quality.

Regression techniques are commonly used to find a model prediction formula. We use a generalized linear model, which is a least-squares fit to an equation of the following form:

$$y = a_1 x_1 + a_2 x_2 + \cdots + a_n x_n + \varepsilon \qquad (2)$$

The x's are site characteristics (such as base voltage or lightning flash density), and the a's are coefficients fitted to the model. The *generalized* linear model is somewhat different from a standard linear model; we used a generalization where the distribution of the error ε is assumed to be a Gamma distribution rather than a normal distribution in a strictly linear model. A Gamma distribution skews to the right, like the log-normal distribution.

We found that the best formula for estimating $\mathrm{SARFI}_{\mathrm{ITIC}}$ is:

$$N_{ITIC} = 4.74 + 0.472 l + 2.47 N_g + 0.192 \frac{n_f \cdot kV^2}{MVA_{xfmr}} + 8.2 \text{ if moderate to heavy tree coverage} \qquad (3)$$

where,

N_{ITIC} = predicted annual number of events which fall under the lower ITI curve

l = total exposure (including three-phase and single-phase portions) on the circuit in km

N_g = lightning ground flash density in flashes/km^2/year

kV = base line-to-line voltage in kV

n_f = total number of feeders off of the substation bus

MVA_{xfmr} = station transformer open-air rating in MVA

If any of the circuit characteristics are unknown, we could use the following medians from the DPQ data:

l = 23.4 km

N_g = 2.57 flashes/km^2/year

$\frac{n_f \cdot kV^2}{MVA_{xfmr}}$ = 25

All three variable terms in the linear regression are significant to at least 99% (there is less than a 1% chance that the terms of the model do not influence the prediction). The tree coverage term is less certain—there is a 9% chance that the term is not significant. We based the tree coverage term on the University of Maryland's Global Land Cover Facility data from the Advanced Very High Resolution Radiometer. Half of the DPQ sites had more than 19% of the land area covered by trees, which we defined as "moderate to heavy tree cover." For the tree coverage term, one could go to the University of Maryland data directly, but we recommend using an educated guess based on first hand knowledge of the site. Leave the tree-coverage term out if there are few trees along the circuit, otherwise, leave include it. For lightning, a flash density map of the US is available in [9], and more specific data is available from lightning detection network providers.

How good is the model? It is "decent" given all the factors that affect sags and momentary interruptions and inherent variability. To get some idea of the variability in the prediction, Fig. 7 shows the actual values observed at each site versus the model predictions. Given the variability of power quality events, it is surprising that the model is this good. 34% of the values are within 25% of the prediction, and 60% of the values are within 50% of the prediction.

For an example 12.47-kV case with three feeders, a 25-MVA transformer, a flash density of 4 flashes/km^2/year, moderate tree coverage, and a total exposure of 32 km, the model predicts 29.8 events per year. For this case, the data shows a prediction interval with a 50% confidence level of between 15.6 and 34.2 events per year (the 90% confidence prediction interval is between 0 and 68.3). The data is dispersed enough that the model is not good enough to use for precision estimates (such as in a contract for premium power).

The site characteristics most affecting sags but not included in this model (from lack of information) are 1) subtransmission exposure and characteristics and 2) percentage of the circuit that was underground.

The best model we found for predicting interruptions is:

$$N_{10} = \begin{pmatrix} 5.52 \text{ if Rural} \\ 0.29 \text{ if Suburban} \\ -1.61 \text{ if Urban} \end{pmatrix} + 0.187 l_3 + 0.27 N_g + \frac{1.24 n_f kV}{MVA_{xfmr}} \qquad (4)$$

where l_3 is the three-phase circuit exposure in kilometers, and N_{10} is the predicted annual number of events with voltage less than 10% of nominal for more than 0.4 seconds.

The parameters differ somewhat from $\mathrm{SARFI}_{\mathrm{ITIC}}$ predictors. Two of the strongest indicators of momentary interruptions are load density and three-phase circuit exposure. Other significant parameters are the lightning activity and a term with voltage, number of feeders, and transformer MVA. The model is not as good as the ITIC model, but all parameters have more than a 95% probability of affecting the result. The site characteristic most affecting momentaries that is not included in the model for lack of information is whether fuse saving is used.

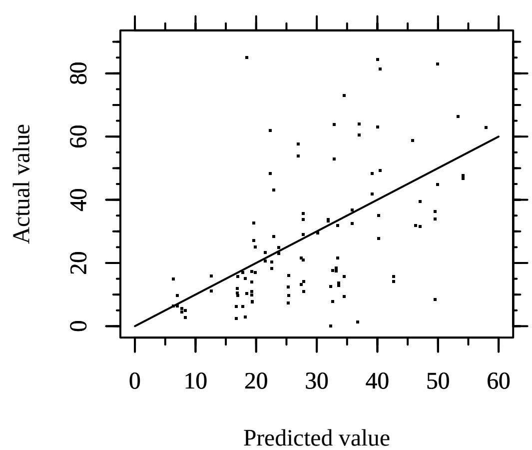

Fig. 7. Actual values vs. predicted values for the model predicting the annual average number of events below the lower ITI curve.

V. Transmission-Level Power Quality

Large industrial customers, utility's prize customers, are primarily fed with transmission-level service and expect high-quality power. Several semiconductor manufacturing sites provided a basis for developing the SEMI F47 standard for semiconductor tools [10]. These sites were primarily served from transmission lines; not all were direct transmission services, but distribution exposure was minimal. While not as extensive as the DPQ study, the monitoring provides good data on the number of events that are primarily from the transmission exposure. Table 4 shows summary statistics from the SEMI dataset of sixteen sites with 30 total monitor-years of data. Fig. 8 compares distributions of SEMI data with the DPQ substation data. As expected, the semiconductor manufacturing sites experience fewer events compared to the typical DPQ site. This comparison provides some guidance on the portion of distribution events that are caused on the transmission system. Use caution though since these are two independent data sets.

Table 4.
Statistics for power quality from the SEMI monitoring study, which are primarily transmission service.

	Average	P(75%)	Median P(50%)	P(25%)
$SARFI_{ITIC}$	4.60	2.05	3.80	5.10
$SARFI_{SEMI}$	2.05	0.00	1.90	3.64
$SARFI_{70}$	4.40	2.05	3.50	5.10
$SARFI_{50}$	0.97	0.00	0.69	1.20
$SARFI_{10}$	0.24	0.00	0.00	0.23

VI. Summary

DPQ sites have widely dispersed power quality. Many sites have many more sags than other sites. Rural sites have many more sags and momentary interruptions than suburban and urban sites. The three strongest indicators of voltage sags are 1) circuit exposure, 2) lightning, and 3) a term with transformer size and number of feeders. A linear model can predict sags based on a small number of site characteristics. Load density and three-phase circuit exposure most strongly affect momentaries. The SEMI data provides some guidance on the portion of distribution events that are caused on the transmission system

VII. References

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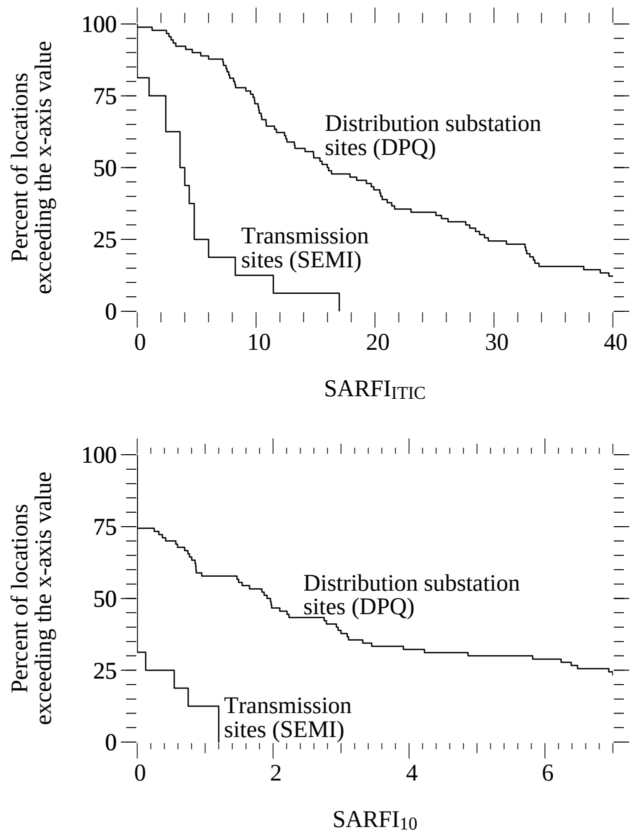

Fig. 8. Comparison of the sixteen SEMI sites with the DPQ substation sites.

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VIII. Biographies

T. A. Short (Senior Member) is with the Schenectady, NY office of EPRI PEAC and prior to that worked for Power Technologies, Inc for ten years. He has been involved in several monitoring projects on distribution systems as well as lightning, voltage sag, flicker, capacitor application, and load flow studies. He received an MS EE degree from Montana State Univ. in 1990.

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W. Sunderman (Member) is a Power Quality Engineer for EPRI PEAC Corporation. Previously, he worked for Square D Company's Power Management Services Group in LaVergne, Tennessee. Prior to joining Square D, he held various positions at Southwestern Electric Power Company. He has experience conducting EMTP studies for utility and industrial power systems.

A. Sundaram (Member) is a Project Manager in the Power Delivery Department at EPRI in Palo Alto, California. Ashok received a BSEE degree from the University of Madras, India, in 1978, an MSEE from Southern Illinois University in 1984. His areas of specialization are power system analysis, electrical machines, control systems, power electronics, and power quality.