THRESHOLD CONSIDERATIONS FOR FARM MITIGATION

An Analysis of ELF-Mitigated Farms in Upper Michigan

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1. Introduction

Research in the sensitivity of farm animals to electric current peaked in the middle 1980s when interest in the dairy farm stray voltage issue was at its highest. The findings reported by researchers such as Dr. R. J. Gustafson at the National Stray Voltage Symposium in Syracuse, New York, in 1984, were that strong behavioral response was obtained from dairy cows at 1.2 V, minimal behavioral response at 0.7 V, and no detectable behavioral response at 0.35 V. Reports such as this led the power industry to adopt 0.5 V as the mitigation threshold.

The ELF project also adopted 0.5 V as the mitigation threshold. IITRI defined the 0.5 V to be a broadband measurement that included both the power and the ELF signals. This was an instinctive carryover from the case of the 6-V neutral safety threshold, where a similar interpretation had been adopted without problems. Little was known about the ambient 60-Hz neutral voltage. IITRI proposed this farm mitigation threshold to the power utilities in Michigan, who readily accepted it, and this threshold was then used as a mitigation goal in the contracts that were agreed to by the utilities and IITRI for ELF interference mitigation.

Farm mitigation was completed in Michigan in 1987, before the ELF antenna was fully operational. There was no opportunity to make a-priori ELF measurements. Farms identified as needing mitigation in Michigan were those within an area where interference was expected based on computer modeling. For this purpose, interference was chosen to be any sign of ELF signal, and 0.1 V was considered the smallest interference voltage to deal with. The interference area boundary dissolves from a clear edge at the higher interference levels into a broad, unfocused boundary at interference levels such as 0.1 V. This simplified the job of shaping the mitigation area by cutting only entire distribution lines or major feeders in and out of the farm mitigation boundary. Power neutral voltage measurements were not considered.

The mitigation of farms in Wisconsin came after that in Michigan. The Wisconsin power cooperatives affected by the ELF antenna at Clam Lake objected to the broadband interpretation of the 0.5-V threshold. The cooperatives wanted to avoid making 60-Hz neutral voltage measurements. There was an aversion on the part of many power utilities at the time to acknowledge the dairy farm issue, because of possible negative public relation and because of the potential liability. The cooperatives persuaded IITRI to redefine the farm mitigation policy in terms that addressed the ELF voltage only. The 0.2-V-ELF threshold arose out of this need, and was based on the rationale that at least 0.2 V of ELF was needed to cause an increase of nearly 10% in the basic 60-Hz voltage, when this was at the industry threshold of 0.5 V.[1] 10% was considered a common sense, minimum contribution before an effect could be attributed to ELF interference. IITRI combined this with the prerequisite that the broadband voltage be above 0.5 V. The resulting criterion is two-tiered: the broadband voltage measurement has to be above 0.5 V, and the ELF (narrowband) voltage measurement has to be above 0.2 V for mitigation to take place.

There are three issues with this two-tiered criterion:

1. The 10% contribution is arbitrary. Some have argued, in similar situations, that <u>any</u> contribution is too much; others reason that 10% is too conservative, and that a contribution of 50% is a fairer level at which to admit responsibility. After all, when the neutral voltage of 0.5 V is increased 50% because of ELF, to 0.75 V, the neutral voltage is still at a level that produces only a minimal response in cows. Finally, still others think that a fairer approach is to tie the ELF level of responsibility to the level of ELF contribution to the problem.

2. This criterion can lead to poor mitigation decisions in marginal cases. For example, a farm with 0.5-V broadband voltage and 0.2-V ELF voltage would be mitigated under this criterion, while a farm with 0.49-V broadband voltage and 0.45-V ELF voltage would not. The fact that this criterion mitigates a farm with only 0.2 V of ELF voltage and does not mitigate a farm with 0.45 V of ELF voltage, while the broadband voltage is nearly the same around 0.5 V, seems a poor decision. The ELF project runs a higher risk with 0.45 V than with 0.2 V.

3. This criterion does not address the uncertainty that is associated with spot measurements. The variability and uncertainty associated with any measurement is just as important to deal with as the number that is chosen to represent the measurement, whether it is spot, time-average, median, etc.

This whole approach to define and resolve the issues is very idealized, based on plausible assumptions of what these voltages are. In fact, it never considers the voltage distribution itself. The following is an examination of actual farm voltages collected in Michigan. The analysis sheds new light on this matter.

2. Michigan Farm Data Analysis

There are 140 designated farms in Michigan that have been tested nearly every year since 1989. The data presented and analyzed here are the historical averages of the primary neutral voltage (V_{pw}) measured wideband with the ELF antenna on, and of the ELF-only primary neutral voltage (V_{pn}) measured using the IITRI Notch Box. The historical average of annual spot measurements is considered the truest and most reliable indication of the neutral voltage at a site.

Figure 1 shows the log-distribution of these two voltages, V_{pw} and V_{pn}, after doing some averaging to transform the true frequency-of-occurrence distributions into smoother functions. The distribution of V_{pw} appears to be log-normal, which is an expected result based on the finding of similar studies in the past. The distribution of V_{pn}, after the log

[1] 0.23 V of ELF is needed to increase the overall voltage precisely 10%, from 0.50 V to 0.55 V.

transformation, is definitively not normal. This peculiar pattern is not the chance result of the farm sample, which is near uniform and random in the mitigation area. Instead, this pattern may be caused by the distribution of the ELF voltage, which is not uniform throughout the area but mound-shaped, with the peak located over the antenna elements themselves. The difference and spread between these two distributions in Figure 1 suggest interesting interactions, which are explored with the scatter plot.

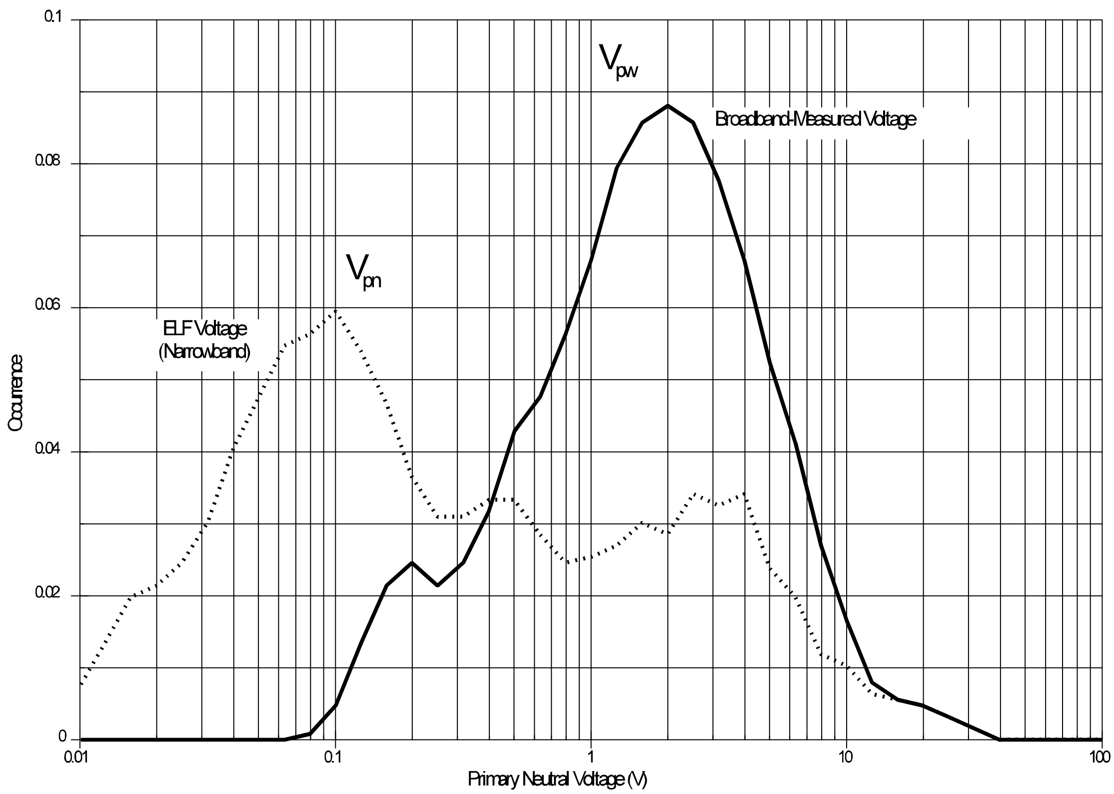

Figure 1. Occurrence distribution of V_{pw} and V_{pn} in Michigan.

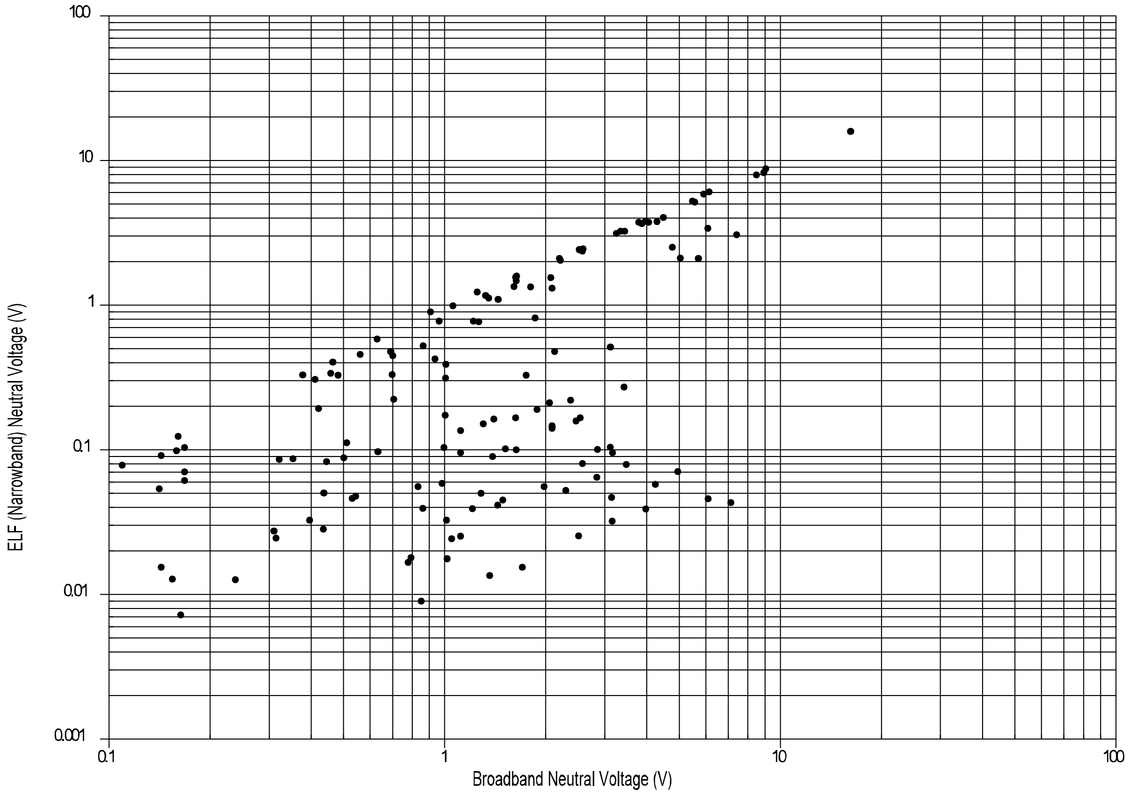

Figure 2. Scatter diagram of V_{pn} (ELF) versus V_{pw} (broadband).

Figure 2 is a log-scale scatter diagram of these farms with V_{pn} plotted against V_{pw}. Sets can be used to visualize graphically the two-tiered criterion, $V_{pw} \geq 0.5$ V and $V_{pn} \geq 0.2$ V, as shown in Figure 3. The scatter area is divided into four quadrants by the lines corresponding to the rule $V_{pw} \geq 0.5$ V and the rule $V_{pn} \geq 0.2$ V.

Looking at Figure 3, farms in quadrant 1 quite obviously have no problem from either the ELF or 60Hz point of view. Farms in quadrant 2 are obviously 60-Hz problems that should be addressed by the power company. Farms in quadrant 3 meet the two-tiered criterion and would be mitigated by the ELF project. The farms in this quadrant tend to fall along a straight line. This is because the broadband and narrowband measurements become equal at the higher voltages; ELF remains the main component when the occurrence of 60-Hz voltage drops off above 5 V.

Quadrant 4 contains a small number of farms, in the lower right-hand corner, that are excluded from mitigation by this criterion. This peculiar grouping in the lower right-hand corner is not a chance event, but the result of the fact that V_{pw} is always higher than V_{pn}. There cannot be any scatter points above the diagonal line $V_{pn} = V_{pw}$.

Figure 3 underscores the shortcoming of the two-tiered criterion in deciding which farms are mitigated and which ones are not mitigated when voltages are low. Most of the farms in quadrant 4, which the criterion excludes from mitigation, present more risk from the ELF perspective than farms in quadrant 3 with $V_{pn} < 0.3$ V.

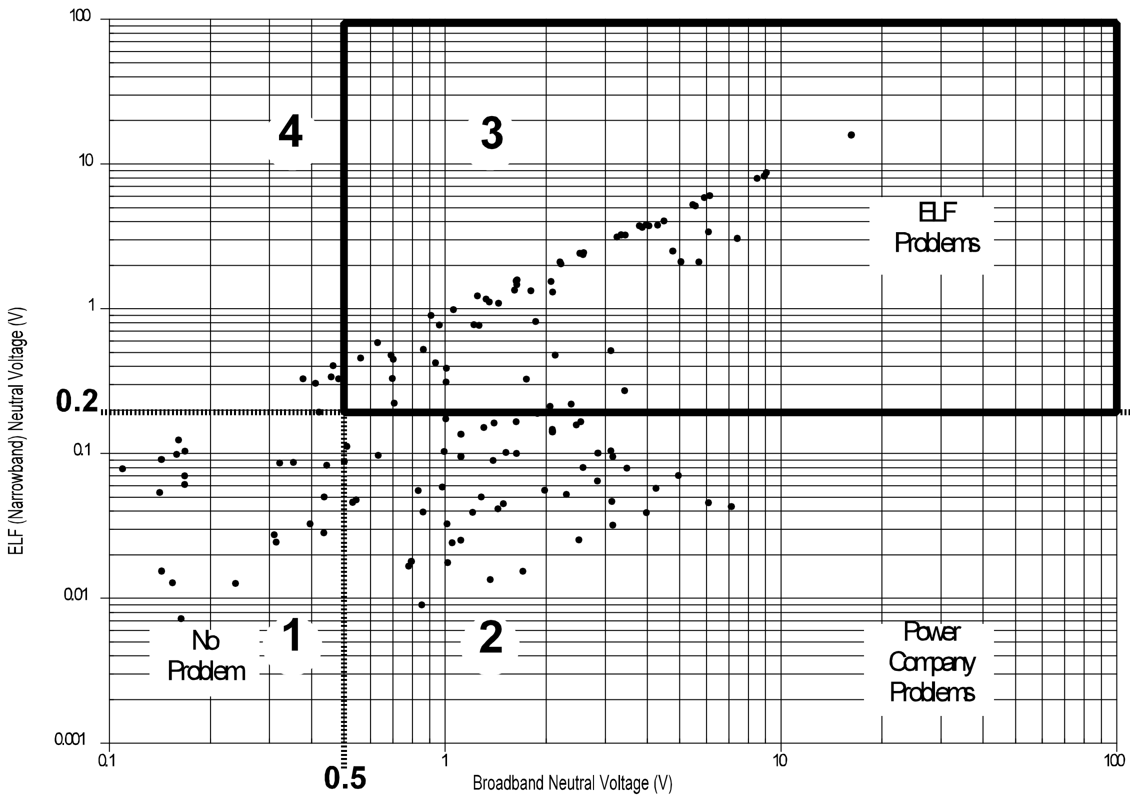

Figure 3. The two-tiered farm mitigation criterion, $V_{pw} > 0.5$ V and $V_{pn} > 0.2$ V.

Can the two-tiered criterion be modified to include farms in quadrant 4? Is there a better rule? The following paragraphs explore these questions.

Figure 4 shows a modification to the two-tiered criterion that includes the farms in quadrant 4 of Figure 3. This new criterion can be viewed as a modification of the two-tiered criterion by rotating the line $V_{pw} = 0.5$ V counterclockwise, pivoting it at the point $V_{pn} = 0.2$ V, $V_{pw} = 0.5$ V. A mathematical description of this criterion includes the equation of an tilted straight line on a log plot, such as the following:

$\text{Log}(V_{pn}) \geq -1 - \text{Log}(V_{pw})$ and $V_{pn} \geq 0.2$ V

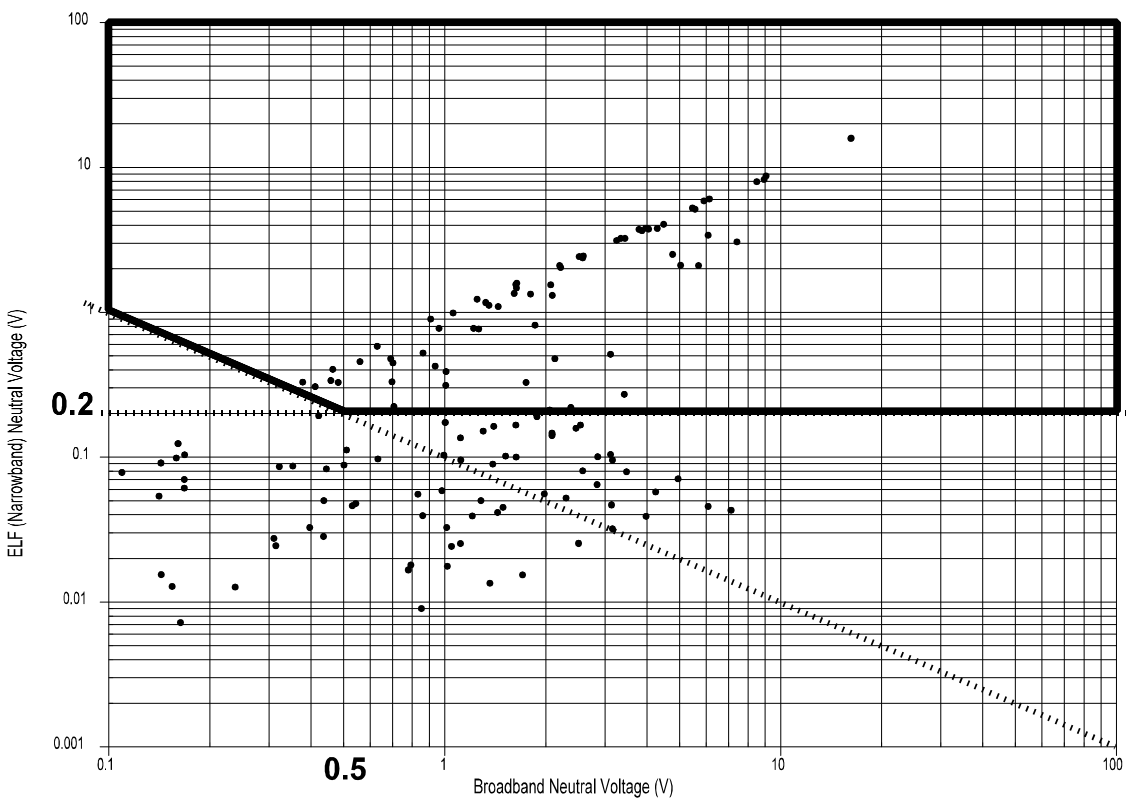

Figure 4. The improved two-tiered criterion, using a sloping line.

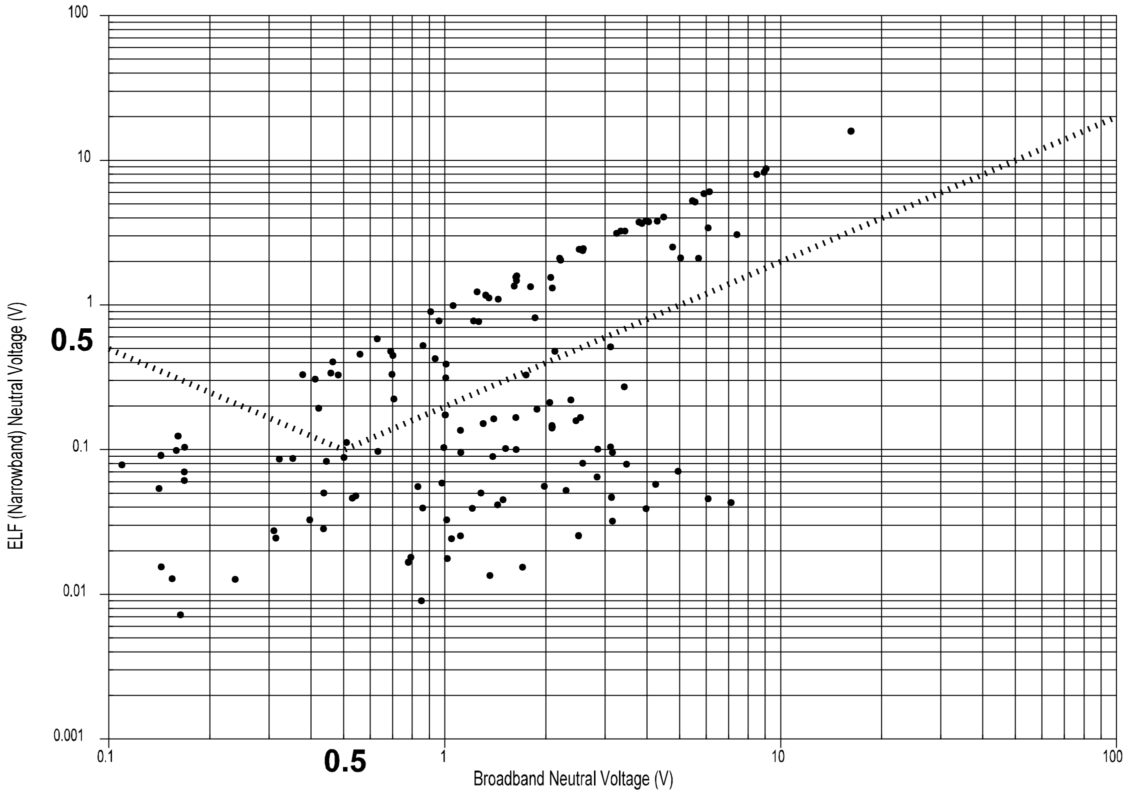

Figure 5. The two-oblique lines farm mitigation criterion.

Pursuing this approach further, one can improve on this last criterion by discriminating against cases where the 60-Hz signal is quite clearly the problem, such as the case where $V_{pw} = 3$ V and $V_{pn} = 0.3$ V. Figure 5 shows graphically how such a criterion would work by using two sloping lines. The point of intersection of the sloping lines in Figure 5 can be moved around to further modify the selection and improve the result.

This approach can be kept up by considering next a three-tiered criterion that would add a horizontal line in Figure 5, to remove the corner. Finally, a curve could be drawn to define the set of farms to be mitigated. The curve hopefully could be described mathematically; for example, using binomials.

The problem with these criteria is that while elegant in their surgical precision of isolating a mitigation set of farms, they are not practical, and have little or no physical interpretation for the user. Furthermore, the improvements in the selection are better qualitatively but few and marginal quantitatively, so there may not be much saving in the number of farms that are mitigated.

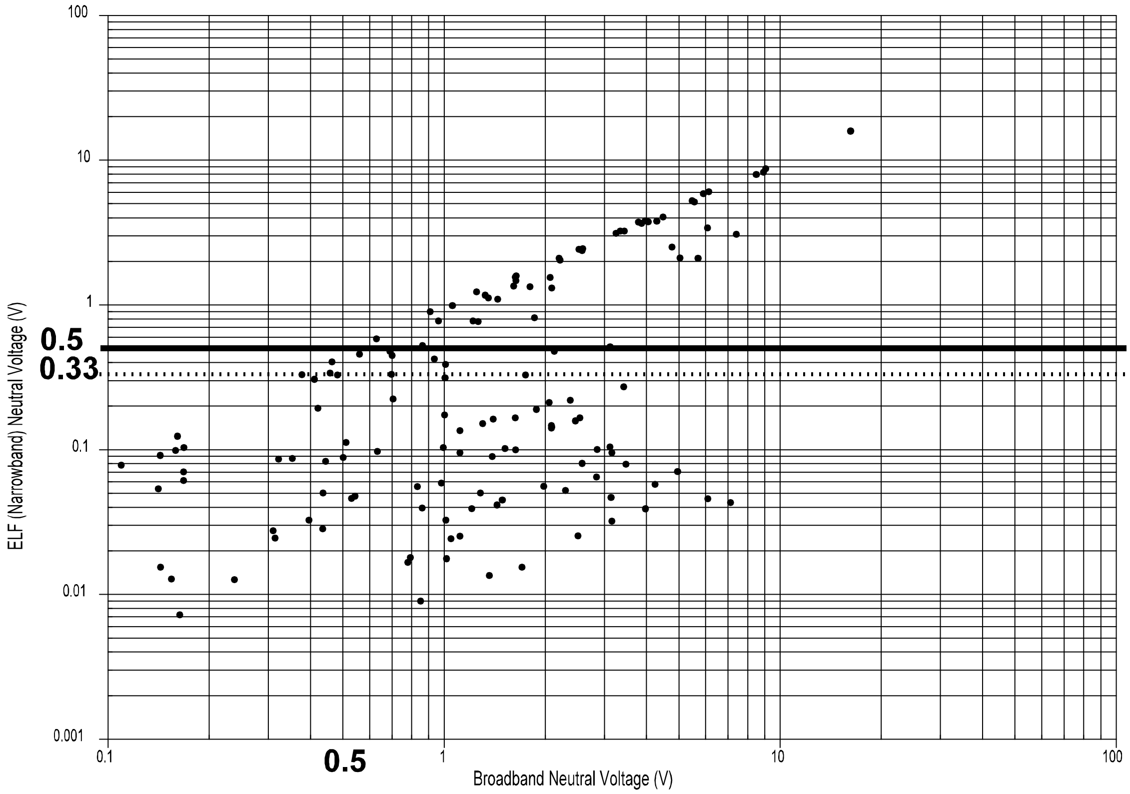

Figure 6. The ELF-only farm mitigation criterion.

Another approach would be to pursue the opposite method, that of simplifying rather than complicating the rules. The two-tiered criterion can be reduced to a single rule by specifying only the ELF voltage at which mitigation is required. Such a criterion is shown in Figure 6 with the V_{pn} threshold set at 0.5 V. This single-rule criterion can be as efficient as many others considered before. Indeed, it can be considered a limiting case of the improved two-tiered criterion with the sloping line of Figure 4, when the sloping line is rotated further counterclockwise to coincide with the horizontal line $V_{pn}=0.2$ V. The reason that this rule works is because the upper left-hand corner of the scatter plot, above the line $V_{pn}>V_{pw}$, is not populated at all. This criterion makes fairer decisions from the ELF point of view and has a simple and common-sense basis.

Picking an ELF threshold voltage for such a simple rule is the next problem; $V_{pn}\geq 0.2$ V comes to mind, of course. However, this threshold is based on an arbitrary consideration, the 10% contribution. $V_{pn}\geq 0.5$ V may be rationalized because 0.5 V is the voltage used by the power industry in deciding mitigation. This rule would be easier to explain to the utilities, because it would be no more than a restatement of how the 0.5 V mitigation voltage specified in the contracts in Michigan is measured.

Some farms that would be mitigated under the two-tiered approach shown in Figure 3 would not be mitigated under this criterion. These are farms with $V_{pw} \geq 0.5$ V and V_{pn} between 0.2 and 0.5 V. The concern is for farms that may have a strong ELF component in this range. One way to relieve this concern is to lower the threshold for V_{pn} to include these farms. The difficulty arises in deciding how much to lower the threshold.

One possible answer comes from looking at the scatter diagram in Figure 2, which shows no points above the line $V_{pn} = V_{pw}$. This line intersects the y-axis at 0.1 V (V_{pn}). This could be a reasonable threshold level for the ELF-only criterion. It is conservative, but it has already been used in Michigan to define the original mitigation area.

A different issue, that of the uncertainty and variability of the measurements, helps to provide another rational answer. The farm primary neutral voltage being used in these criteria is either a spot measurement, a time-average measurement, or some other representative number derived by some established rule or method. As such, it will necessarily be encumbered with some uncertainty. To err on the conservative side, the highest anticipated voltage would be used in the criterion. However, this value is seldom known and is very difficult, even impossible, to determine. The historical variability at other locations in the area can be used for the unknown variability at a specific farm. We already know this historical variability from a statistical variability analysis of the spot measurements made over four years at each of the 1300 mitigated locations in Michigan. The primary neutral measurements of mitigated power services in Michigan fall within ±48% of the respective historical averages at these sites, with 95% certainty. By reciprocity, one can achieve an effect similar to that of using the highest anticipated spot measurement by applying the conservative correction for the uncertainty to the threshold itself, and lowering it. Lowering the 0.5-V threshold level by the historical uncertainty margin (i.e., dividing it by 1.48), yields the new threshold level of $V_{pn} = 0.33$ V. This level incorporates the uncertainty that exists with spot measurements and achieves the other objective of reconciling a bit more the results of the two-tiered rule of Figure 3 to the single rule of Figure 6.

Table 1

Item	Description	Farms
A	Farms in Michigan	140
B	$V_{pw} \geq 0.5$ V	114
C	$V_{pw} \geq 0.5$ V and $V_{pn} \geq 0.2$ V	61
D	$V_{pw} \leq 0.5$ V and $V_{pn} \geq 0.2$ V	5
E	$V_{pn} \geq 0.5$ V	48
F	$V_{pn} \geq 0.4$ V	54
G	$V_{pn} \geq 0.33$ V	57
H	$V_{pn} \geq 0.3$ V	62
I	$V_{pn} \geq 0.2$ V	66
J	$V_{pn} \geq 0.1$ V	85

Table 1 is a breakdown of the farms in Michigan that gives a numerical perspective to the issues discussed so far. Of the 140 farms in Michigan, 114 (81%) have a broadband voltage above 0.5 V. Item C is the two-tiered criterion used in Wisconsin, which yields 61 farms in Michigan. Item D is the number of farms in quadrant 4 of Figure 3, which are excluded from mitigation by the two-tiered criterion. Items E to J show different threshold levels for the ELF-only criterion and the corresponding number of farms that would be mitigated.

The modified two-tiered criterion of Figure 4 that includes the farms of quadrant 4 in Figure 3 includes the farms in items C and D, a total of 66 farms. This corresponds to item I, which is the ELF-only criterion with the V_{pn} threshold set at 0.2 V. By comparison, the ELF-only criterion yields 48 farms with $V_{pn} = 0.5$ V, and 57 farms with $V_{pn} = 0.33$ V.

The effect of changing the threshold level in the ELF-only criterion is to change the number of farms mitigated in an almost linear fashion for V_{pn} between 0.2 V and 0.5 V. Any thresholds in the 0.1 to 0.5 V range can probably be justified without much difficulty; the difference is just a few farms. The justification for the threshold level loses some of the interest.

The most conservative threshold for the ELF-only criterion appears to be $V_{pn} = 0.1$ V, which is what was used originally in Michigan in the computer interference prediction. Actual measurements show that 85 of the 140 farms mitigated in Michigan would meet this criterion with the antenna being operated as it is at present. Without actual information on other antenna operating modes, most of the mitigated farms in Michigan would have to be kept mitigated with the ELF-only criterion threshold set at $V_{pn} = 0.1$ V.

3. Conclusions

The issue of an ELF farm mitigation threshold or criterion has been revisited, this time with the perspective given by examining an actual sample of field measurements collected in Michigan. This study is predicated on the assumption that the decision to mitigate is based on a single, representative voltage number for the farm, which can be a spot measurement, a time-average measurement, or some other type of representative quantity.

The scatter plot of the ELF-only voltage measurements (V_{pn}) versus the broadband voltage measurements (V_{pw}) has been helpful in identifying a key pattern in the data: the fact that the farms do not fall at random throughout the plot; instead, they tend to fall along a $V_{pn}=V_{pw}$ line at the higher voltages, while they spread out below this line at the lower voltages, where the 60-Hz component dominates (a comet-tail pattern).

A number of rules have been considered to see how well they do the job of isolating the set of farms that need mitigation. These include the two-tiered criterion used in Wisconsin, and others that use specially defined lines to create more effective decision boundaries. The more complex rules do a better job by minimizing the number of poor decisions in borderline cases. However, they are too esoteric to use, not intuitive at all, and produce little savings in terms of eliminating farms that should not be mitigated.

The ELF-only threshold, although counter-intuitive, turns out to be a simple, practical, and efficient rule. This is because of the grouping of the farms below the line $V_{pn} \leq V_{pw}$ on the scatter plot. With one stroke, the ELF-only threshold recognizes all ELF concerns while discriminating against cases where 60-Hz is the main problem. An official threshold of $V_{ELF} \geq 0.5$ V would require no major change in the contracts with the utilities, and would, therefore, be received with no apprehension. A design threshold of $V_{ELF}=0.33$ V could be used for engineering decisions; it would offer a conservative edge that addresses both the uncertainty of the measurements and the concern with some marginal farm cases.

There is no perfect rule, and judgment has to be exercised every time in interpreting the data and applying the rule. The approach laid out above allows for plenty of flexibility in reviewing individual cases, while the committed goal remains $V_{ELF} \geq 0.5$ V. The important development here is that the 60-Hz factor seems to have dropped out of consideration for ELF farm mitigation.