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A Study of Continuous PQ Disturbance Levels in MV/LV Distribution Systems

Victor J. Gosbell
University of Wollongong, victor_gosbell@uow.edu.au

D A. Robinson
University of Wollongong, duane@uow.edu.au

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Abstract

Distribution Network Service Providers need to be aware of the general variation of PQ disturbances across their network, from the sites as diverse as the MV bus bar of a zone substation, the end of a MV feeder, and at the near and far ends of LV mains. This paper develops an understanding of PQ variations across such a system from survey results correlated with approximate analysis used to assign a PQ disturbance ranking to each site. The work will concentrate on continuous PQ disturbances, defined as those due to load current effects, for example voltage deviations, unbalance, fluctuations and harmonics.

Keywords

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A STUDY OF CONTINUOUS PQ DISTURBANCE LEVELS IN MV/LV DISTRIBUTION SYSTEMS

Victor GOSBELL, Duane ROBINSON
Integral Energy Power Quality Centre
University of Wollongong - Australia
duane@uow.edu.au

Summary

Distribution Network Service Providers need to be aware of the general variation of PQ disturbances across their network, from the sites as diverse as the MV bus bar of a zone substation, the end of a MV feeder, and at the near and far ends of LV mains. This paper develops an understanding of PQ variations across such a system from survey results correlated with approximate analysis used to assign a PQ disturbance ranking to each site. The work will concentrate on continuous PQ disturbances, defined as those due to load current effects, for example voltage deviations, unbalance, fluctuations and harmonics.

INTRODUCTION

Distribution Network Service Providers are increasingly interested in obtaining an understanding of the actual Power Quality (PQ) disturbance levels in their network. Pressure from regulators to provide evidence of PQ targets being satisfied and a growing awareness amongst a more educated customer base also ensure the need for proactive monitoring of PQ disturbance levels. Data obtained from such PQ monitoring campaigns may also be used to help Service Providers plan for future network improvements or developments. There is a move towards the installation of fixed PQ monitors at selected sites with accompanying communications and database facilities. However, the infrastructure required to enable such installations is usually capital intensive and thus is only slowly being adopted.

It is not yet practicable to monitor all sites that might be of interest and an approach needs to be developed for determining a short list of critical sites that ought to be monitored in the first stage of an evolving monitoring campaign. These sites should be selected so that their limited data gives an unbiased view of the network's overall PQ disturbance levels. In this way only a limited number of sites are required to give an estimate of the overall PQ disturbance levels throughout the network.

To further develop a methodology of ranking sites according to levels of PQ disturbances first described in [1], the method is utilised in this paper and correlated to actual field results from a study section of a study distribution system. For the theoretical work approximate analysis is used as although a more accurate simulation may be completed using software packages, such as PSCAD/EMTDC [2], the system parameters from the MV busbar of a zone substation, the end of a MV feeder, and at the near and far ends of LV mains will vary considerably from system to system. This paper will concentrate on continuous PQ disturbances, defined as those due to load current effects including voltage deviations, unbalance, fluctuations and harmonics. The work is completed as part of ongoing research by the Integral Energy Power Quality Centre into improving PQ monitoring methodology and reporting procedures.

STUDY DISTRIBUTION SYSTEM

To obtain a better understanding of the propagation characteristics of continuous PQ disturbances throughout electricity distribution systems a survey was completed on a section of a study system. Five PQ monitors were strategically placed on part of an MV/LV distribution system for two weeks, with one at the MV level and four at the LV level. Three of the LV monitors were placed at the terminals of LV transformers and it will be shown are able to give some estimate of the MV levels also. This approach uses the distribution transformer as a voltage transformer to access the MV system away from the zone substation where there are no voltage transducers fitted. The validity of this approach is confirmed by simultaneous measurement of MV and LV levels at the zone substation.

The monitoring campaign at the study distribution system was completed over a two week period. The choice of a two week monitoring period is appropriate for the continuous disturbances and allows the basic weekly repetition cycle to be checked. For a complete analysis seasonal effects on PQ disturbances levels should also be considered to ensure monitoring has not captured data from a season which produces lower PQ disturbance levels, i.e. the intensive use of single phase air conditioners during summer months may introduce much higher voltage fluctuation indices on some LV distributors. Seasonal effects may be better analysed when fixed PQ monitors become more commonplace.

Three types of relatively inexpensive PQ monitors were used for the study PQ monitoring campaign. A total of seven monitors were used for the five sites. Two monitor types were connected in parallel at two sites for a comparison of different manufacturers of PQ monitors while also providing a more complete functionality for recording PQ disturbances. As the monitors were relatively low cost, functionality such as measurement of short term flicker indices was not available on all instruments. In this way the connection of two monitors allows for a more complete set of data to be obtained although a monitor with a more complete set of functionality (usually more expensive) would be preferred.

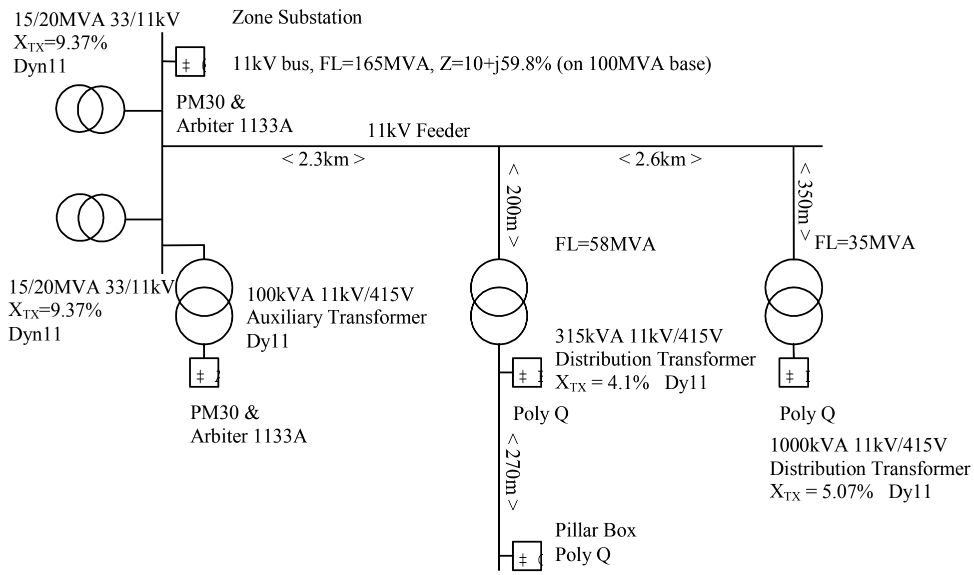

Figure 1: Study distribution system schematic layout

A layout of the study system selected is illustrated in Figure 1. Approximate fault levels, feeder lengths, PQ monitor types and transformer parameters are included with the PQ monitor locations Sites 1-5. The system is radial in nature which is typical of a majority of distribution systems within Australia (not including some CBD locations). The tee-off points along the 11kV feeder where distribution transformers are connected are not shown other than for the locations monitored.

The study system was selected to have parameters which closely match what is assumed to be typical values for most distribution systems in Australia, although these will vary somewhat from utility to utility. Typical values include a 11kV bus bar fault level of 100-250MVA, feeder lengths of approximately 5km, distribution transformers sizes of 100-1000kVA and LV distributor lengths of less than 500m.

VOLTAGE DISTURBANCE FIGURE

For the study system illustrated in Figure 1 the monitoring locations selected were given a PQ disturbance ranking using the methodology outlined in [1]. The PQ disturbance ranking of the site is referred to as the Voltage Disturbance Figure (VDF) with a higher number indicating predicted higher PQ disturbance levels.

To use the approximate analysis method to find the VDF the following conditions are assumed [1]

(i) PQ disturbances arise from a combination of upstream levels and load currents interacting with the system impedance.
(ii) PQ disturbances from individual loads sum arithmetically.
(iii) Individual loads contribute the same level of PQ disturbance relative to their fundamental current.
(iv) No significant phase diversity exists.

The VDF is calculated by assigning equivalent lengths to each part of the distribution system including overhead lines, transformers, etc. weighted by the loading. The calculation is similar to a load flow but much simpler. The equivalent lengths are converted into Voltage Disturbance Increments (VDI) which are summed together to give the VDF.

It is proposed that the calculation of a VDF for various points within a distribution system would allow a Network Service Provider to identify optimal locations for placement of PQ monitors for a preliminary assessment of PQ disturbance levels.

Figure 2 illustrates the VDF calculated for each PQ monitor location within the study system versus the distance from the source. The distance is not shown to scale however the predicted ranking of sites is clearly visible with all LV sites showing higher predicted PQ disturbance levels than any part of the MV system.

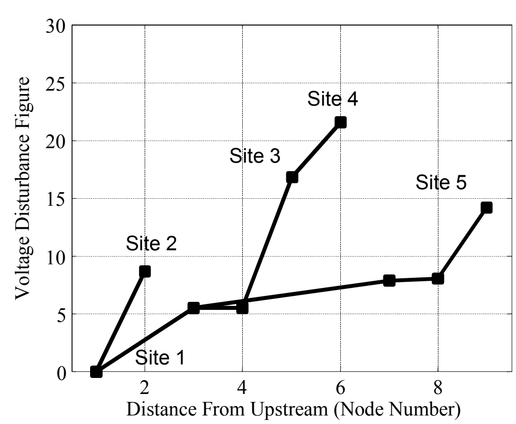

Figure 2: VDF distribution for study system

The order, from highest to lowest, of the monitoring locations according to their VDF is Site 4, Site 3, Site 5, Site 2, and finally Site 1. Thus it is expected that Site 4 will have the highest PQ disturbances levels. Site 1 is assumed to have a VDF of zero. In practice, background levels from upstream will add approximately equal offsets to the VDF, but this should not have a great impact on ranking.

PQ SURVEY RESULTS

RMS voltage. The 10 minute average rms voltage was recorded every 10 minutes at each of the five monitoring locations. This was recorded to determine the amount of rms voltage variation thus identifying the success of the voltage regulation applied throughout the distribution system. For the study system an automatic tap changer is located at the HV/MV zone substation transformer and manual tap changers are located on the MV/LV distribution transformers. The variation between individual phases was also of some interest with regards to ensuring phases are loaded equally [3].

Reporting the rms voltage regulation was completed for individual phases for this monitoring program. In larger monitoring campaigns this may be seen as an excessive amount of information to present and perhaps only the average of the three phases would usually be reported [4]. A quick check of the correlation between the individual phase using a scatter graph as shown in Figure 3 is a relatively good indication as to whether all phases need to be reported individually.

Figure 4 illustrates the maximum, minimum, and mean rms voltage levels recorded for each of the sites within the study system over the two week period. The 97.5th percentile and 2.5th percentiles are also included to illustrate the voltage extremes which are only exceeded 5% of the time. As MV levels appear on the same figure as LV voltage levels the rms voltages are reported as a percentage of nominal. The target voltage ranges for this system are considered to be 11kV ±6% for MV, and 230V +10/-2% for LV (this unusual percentage is due to Australia recently transitioning from 240V to 230V). The LV nominal voltage can be expressed approximately as 239.2V ±6%.

In Figure 4 Site 5 is shown to be out of the specified limits, however this is due to the customers being located further down a considerable length of LV distributor rather than close to the MV/LV distribution transformer, where the voltage appears at a much higher level. All other sites where found to lie within the specified limits.

The use of off nominal tap changers largely determines the magnitude of the rms voltages appearing on the distribution system. These are set to give a suitable voltage profile along the LV distributors rather than providing the nominal voltage at the transformer terminals. Thus it was not expected to be able to rank sites according to their maximum, minimum or mean voltage. There will still be a component of voltage drop due to impedance and load current effects and thus ranking of the sites according to rms voltage is achieved by comparing the amount of voltage deviation from the measured mean voltage level for each phase [1].

Ranking the sites according to the amount of voltage variation, illustrated in Figure 5, gives the order Site 4, Site 3, Site 5, Site 2, Site 1 which correlates well with the theoretical ranking provided by the VDF. This is expected as the randomness of customer loadings increases as we move further along the LV distributor.

Voltage Unbalance. Directly recording the average voltage unbalance over each 10 minute interval was only available as a functionality on one type of instrument used in the monitoring program. This type of instrument was installed only at Site 3, Site 4 and Site 5. Thus a full comparison of sites with respect to voltage unbalance could not be completed using the 10 minute average of the voltage unbalance. For the three sites having instruments with the unbalance functionality available general agreement for the 95th percentile unbalance with the VDF was obtained with Site 3 and Site 4 giving a slightly higher level of unbalance than Site 5.

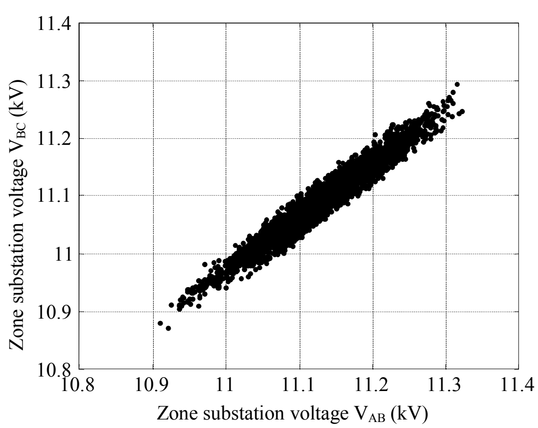

Figure 3: Scatter graph of zone substation rms voltages

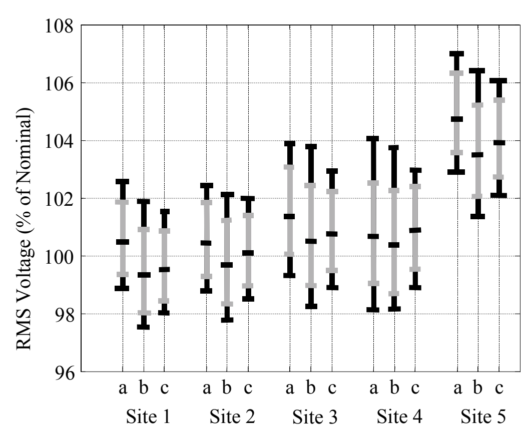

Figure 4: RMS voltage maximum, 97.5th percentile, mean, 2.5th percentile, and minimum for study system

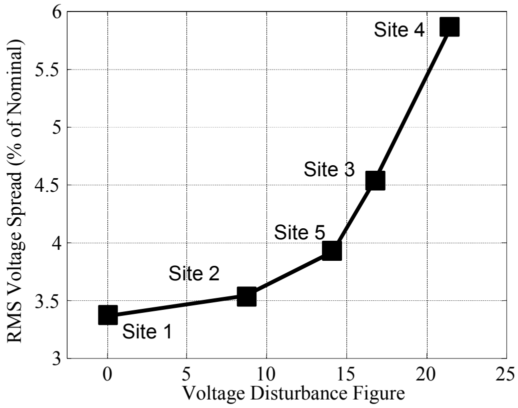

Figure 5: RMS voltage variations from mean versus VDF

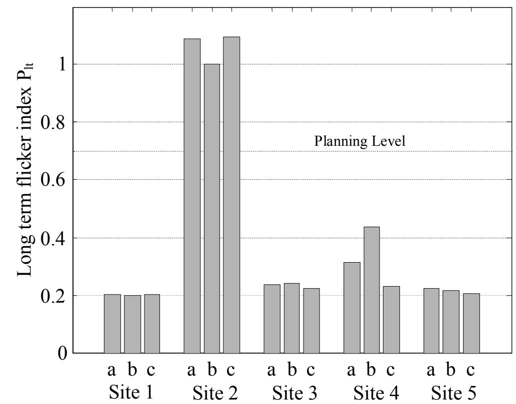

Figure 6: RMS voltage variations from mean versus VDF

Voltage Fluctuations. The short term flicker index P_{st} was also recorded every 10 minutes at each of the monitoring locations. From these recordings the long term flicker index P_{lt} was also calculated. The relevant voltage fluctuation standard AS/NZS 61000.4.7 [5] suggests using the 99th percentile of these values over the period of one week to evaluate voltage fluctuations, however as P_{lt} is only calculated every 2 hrs this equates to the 2nd highest value of P_{lt} over the week, thus questioning the use of such a statistical value. For the ranking of sites the 95th percentile is used and is illustrated in Figure 6. As with the rms voltages short term and long term flicker indices are recorded for individual phases. However, reporting the maximum 95th or 99th percentile of each of the three phases is generally sufficient.

According to the results illustrated in Figure 6 for voltage fluctuations it seems a large component of the LV voltage fluctuation levels are due to the upstream contributions. At Site 2 the fluctuations are largest due to the use of mains signalling injection devices, however these fluctuation do not seem to transfer significantly to the other LV sites.

Voltage Harmonics. The propagation of harmonics in distribution systems has been studied by [6] using detailed simulations concluding that harmonic power flow was difficult to follow with each system needing to be studied individually. For purely radial systems with limited or no PFC capacitors connected it has been proposed that estimating harmonic voltage levels using approximate analysis can be completed with satisfactory results [7]. In [1] the voltage THD measured on a system was shown to generally agree with the calculated VDF ranking. Of all the PQ disturbance types it was expected that voltage harmonics would give the best results when ranking sites. This is due to the assumptions made in the VDF calculation being very similar to those used for "back-of-envelope" harmonic analysis.

For this study system voltage THD, even and odd harmonics up to the 10th, and all the odd harmonics up to the 40th harmonic were recorded for each phase. The voltage harmonics were recorded at each of the sites every 10 minutes. The actual value of harmonics recorded differed slightly according to the instrument used, with some instruments recording a full 10 minute average and others recording only a short snapshot every 10 minutes. This is not seen as a large disadvantage as it was found that most harmonics were reasonably steady state over such periods and thus readings from the various instrument types were able to be compared with confidence.

In reporting harmonics only the maximum from each phase and the maximum of the 95th percentiles were presented. To establish the available 'head room' until the limits are reached, the harmonic voltage as a percentage of the harmonic planning level has also been found to be useful.

For the survey of the study system all harmonics were less than 50% of the indicative MV planning levels as recommended by AS/NZS 61000.3.6 [8]. An interesting finding was that over 75% of the harmonic voltage at the end of the LV distributor appears to come from upstream. This is illustrated in Figure 7 where the MV harmonic levels for THD, 5th and 7th harmonics are at approximately 75% of the harmonic voltage levels at Site 4. This occurs even though the harmonic impedance of the LV distributor accounts for approximately 40% of the total harmonic impedance seen by the LV customer. Light loading of the LV distributor and the cumulative effect of many loads combining their harmonic currents at the HV/LV transformer will also contribute to the relatively high upstream value of harmonic voltage.

Figure 8 illustrates the correlation between the 95th percentile 5th harmonic, 95th percentile THD and the VDF for the study distribution system. As expected a high level of correlation has been obtained. Further surveys are required to establish if the method is still applicable to distribution systems containing significant PFC capacitors.

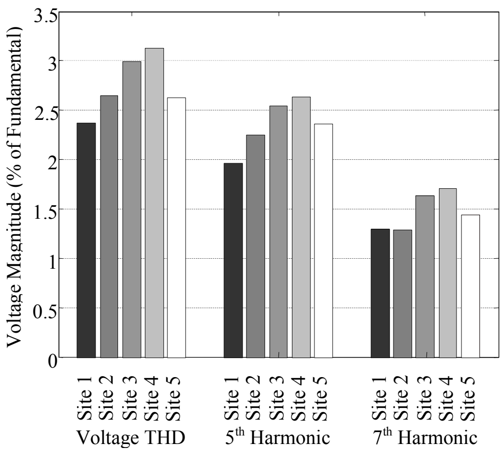

Figure 7: Harmonic voltages and THD for study system

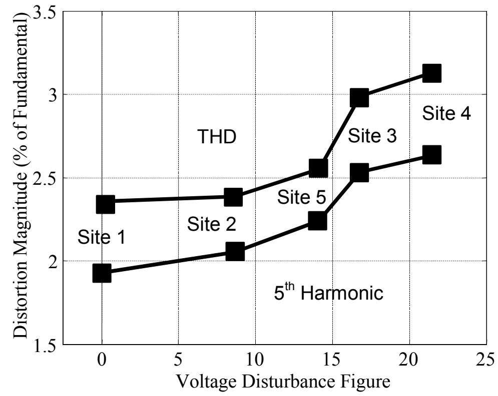

Figure 8: 95th percentile harmonics versus VDF

CONCLUSION

A PQ monitoring program has been carried out at various points along a distribution system feeder. This paper has shown how the extensive volume of recorded data from such a monitoring program can be systematically analysed to show the dispersal of PQ disturbance levels across the distribution system.

A simple method of ranking sites using a number of simplifying assumptions has been shown to be a useful tool in selecting sites where PQ monitors will be best utilized and also may be extended to predict PQ disturbance levels in other parts of the distribution system. Some of the notable findings of the PQ monitoring program results and the site ranking calculations were

(i) PQ levels increase from the zone substation out to the ends of the LV mains.
(ii) About 75% of the level of PQ disturbance appears to come from upstream.
(iii) Unbalance and harmonic levels propagate in a similar manner. Voltage levels do not propagate in the same way because of the effect of off-nominal transformer taps.
(iv) When sites are ranked from best to worst, all LV sites are worse than MV sites.
(v) The ranking of a site can be estimated with good accuracy from a simple analytical approach.

It is proposed that the simple analytical approach presented allows the estimation of the continuous PQ disturbance levels with sufficient accuracy to give a guide to monitor placement. Further work is required on much larger systems to verify the method.

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