DEVELOPMENT OF A SOFTWARE TOOL UNDER AS61000.3.7, TO PROVIDE ASSESSMENT OF VOLTAGE FLICKER CAUSED BY FLUCTUATING LOADS

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ABSTRACT

AS61000.3.7 "Emission Limits for Fluctuating Loads in MV and HV Power Systems" *was introduced as the governing standard in Australia and New Zealand in 2001, for the assessment of flicker in MV and HV systems. Unlike the previous Australian Standard, no software currently exits to assess loads under AS61000.3.7, and so the aim of this paper is to define and develop such a tool. The software tool must provide assessment of voltage flicker under the standard, emitted by a range of common fluctuating loads. This software tool is hoped to aid application and acceptance of the standard within the power utility industry.*

1. INTRODUCTION

With increasing customer expectations and with challenges such as industry deregulation, power distribution authorities face an increasing need to focus on the power quality of their distribution network. The accurate measurement and assessment of voltage flicker is an essential part of this focus, and an area highlighted with the introduction of the AS61000.3.7 standard.

The introduction of AS61000.3.7 "Emission Limits for Fluctuating Loads in MV and HV Power Systems" [1], as the new governing Australian and New Zealand Standard, has provided opportunity for enhanced flicker assessment, but the lack of applicable software and engineering exposure has limited the application of this standard within the industry.

The AS61000.3.7 standard is based on the IEC 61000.3.7 document [2], which has found acceptance across Europe and is currently being reviewed for implementation by the IEEE in the United States and Canada [3]. AS61000.3.7 provides an accurate assessment of the flicker produced by various fluctuating loads, and considers several network factors such as existing flicker levels, and the operation of multiple machines in its assessment.

The aim of this paper is to develop a software tool to assess flicker, under AS61000.3.7 requirements, which will be appropriate for implementation within an electricity distribution organisation, and that can be applied to fluctuating load types typical to a distribution network.

2. ASSESSMENT OF VOLTAGE FLICKER

2.1. OVERVIEW

AS61000.3.7 defines three independent stages of assessment for voltage flicker. The three defined stages of assessment are as follows [1].

- Stage 1 – "Simplified Evaluation of Disturbance Emissions"
- Stage 2 – "Emission Limits Proportional to the Agreed Power of the Consumer"
- Stage 3 – "Acceptance of Higher Emission Levels"

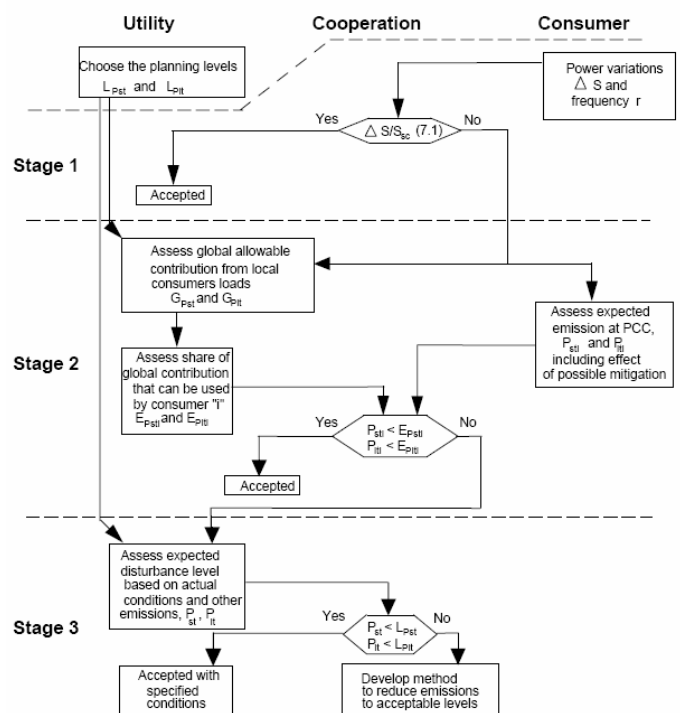Figure 1 details the assessment process.

Figure 1 - "AS61000.3.7 assessment process", taken from [1]

The flicker caused by a load, which passes any of these three assessment stages, may be considered acceptable.

Loads are generally assessed in terms of their 'Short/Long Term Flicker Severity', which is an indicative value, derived from site measurements, or which can be calculated/predicted. Throughout this document, HV refers to 'High Voltage Loads' (35-230kV) and MV refers to 'Medium Voltage Loads' (1-35kV) [1].

2.1.1. STAGE 1 ASSESSMENT

This is a simple assessment of flicker. If the apparent power fluctuation of the load (called ΔS), is small in comparison to the system 'Short Circuit Capacity' (S_{sc}), then the load is considered acceptable and may be connected to the network. What is determined as 'small' for MV is defined in Table 4 of the standard, shown below, or from Equation 9 of the standard for HV loads. The number of voltage changes per minute is also considered within the MV flicker assessment.

r min^{-1}	$K=(\Delta S / S_{sc})_{max}$ (%)
r > 200	0.1
$10 \leq r \leq 200$	0.2
r < 10	0.4

Figure 2 – "AS61000.3.7 Table 4, MV Flicker Limits" taken from [1]

2.1.2. STAGE 2 ASSESSMENT

Stage 2 is a more detailed assessment than Stage 1. It evaluates flicker in regard to the absorption capacity of the network, and considers the flicker emissions proportional to the users network demand. Thus, a user owns a share of the network flicker capacity, proportional to their share of the network demand, and cannot exceed this capacity with their emissions.

Assessment is performed by calculation of a parameter known as the 'Individual Users Emission Limit', and then the user's 'Flicker Severity' is assessed against this parameter. If the consumer's flicker severity is less than their emission limit, the load can be connected to the utility. Calculation of the 'Individual Users Emission Limit' requires definition of network parameters known as 'Planning Levels', and 'Transfer Coefficients', and requires knowledge of load magnitudes, and the users' proportion of the network supply. The load flicker severity must be measured at the site, or predicted using the method described in Appendix A of the standard [1].

2.1.3. STAGE 3 ASSESSMENT

While assessment stages 1 and 2 are largely mathematical and decisive, Stage 3 assessment is largely at the discretion of the planning engineer.

Stage 3 Assessment involves investigation of alternative connection options for the load, or determination of spare flicker capacity in the system. Thorough and accurate site and network investigations must be carried out and all viable options investigated. This stage will involve a great deal of negotiation between the customer and utility, and may result in system upgrades, load modification, or rarely, acceptance of higher emission levels. This last option, however, is not recommended.

2.2. PREDICTION OF LOAD SEVERITY

Appendix A of the standard defines a simplified method of predicting the flicker severity of a fluctuating load. Use of this method is necessary for theoretical load connections, or where it is not possible - or practical - to measure the flicker emitted by a fluctuating load.

Flicker curves and calculations are often based on what is known as 'Regular Rectangular Voltage Change', which is a voltage change waveshape that is rectangular when plotted against time. The method described in Appendix A of the standard introduces a series of 'Shape Factor' graphs, which relate less standard voltage-change waveshapes to more familiar rectangular shapes. Several formulas can then be used to derive a short/long term flicker severity from these results, which can then be used for assessment.

This simplified prediction method is seen as integral in providing accurate assessment of various complex load types; for this reason, it was included within the software tool.

3. LOADS CONSIDERED IN THIS STUDY

The standard can be applied to the assessment of any load if adequate information about its operation is available. For example, induction motor loads under various starting schemes are well understood, are easy to model, and will be a large proportion of loads that require flicker assessment. Other load types such as Arc-Furnaces, Draglines, Crushers, Rollers, etc, will all be grouped under the category of 'Complex Loads'. To enter complex load information into the tool, two further categories have then been defined, depending on the information available about the load operation. They are:

- DATA KNOWN: Which refers to the load apparent power fluctuation and number of voltage changes per minute.

- SHAPE KNOWN: Which refers to the system voltage or power fluctuation, caused by the load, and the corresponding number of voltage changes per minute.

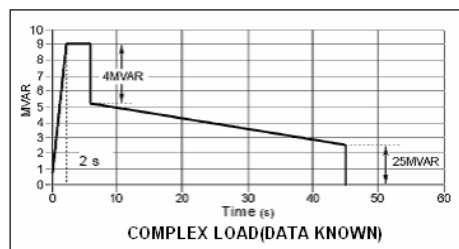An example of these two data formats are shown in Figures 3 and 4 respectively.

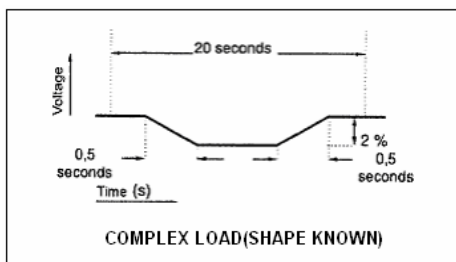Figure 3 – "An example of complex load (data known)" adapted from [1]

Figure 4 – "An example of complex load (shape known)" adapted from [1]

Using these defined categories, load data can be entered into the tool, and then assessed using the same process for each load type. Any load or combination of loads can be defined through these categories.

4. NETWORK MODELLING

Under the standard, assessment procedures for MV and HV flicker-producing loads vary subtly. Both follow the same process, but utilise different calculations. It should be noted that Low Voltage (<1kV) loads have not been considered in this study. It should also be noted that although flicker can propagate through several parts of a power system, only certain network elements need to be considered in the flicker assessment process.

The network that has been used for flicker assessment case studies is shown in Figure 5. It is an equivalent circuit of the network from the appropriate substation to the 'Point of Common Coupling' (PCC) of the consumers load. The 'appropriate substation' is a Zone substation for MV and a Bulk Supply Substation for HV. The substation has been chosen as the first component of the equivalent model because there is generally accurate data available relating to substation 'Infinite Bus Impedances', representing the network behind this point.
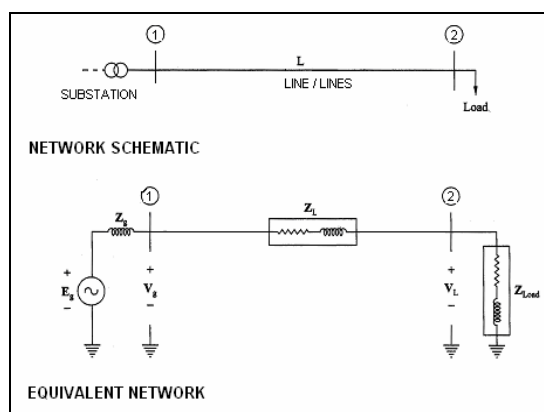

Figure 5- "Network considered for case studies"

The 'Infinite Bus Impedance' represents the equivalent network behind the substation, as a single equivalent impedance, greatly simplifying calculations. Conductors and lines have been considered using the series impedance model, also simplifying to a single equivalent impedance.

In this way, the entire network can be combined and represented as single complex impedance value (Thevenin's impedance), which can be used for calculation of the parameter S_{sc}, the network short-circuit

capacity at the PCC, allowing for the assessment of loads under the standard.

5. SOFTWARE TOOL CONSTRUCTION

5.1. SELECTION OF PROGRAM

Several programs were reviewed for the construction of the software tool, and the 'Microsoft Excel' program was chosen. This decision was made due to the simplicity of coding of Excel, and its ability to hold large amounts of data. It was also considered an advantage of Excel that different assessment stages could be placed on different sheets, with the facility of easy navigation between various sheets. 'Visual Basic for Applications' code was also utilised within these sheets, to give the tool a professional appearance and operation.

5.2. GENERAL SOFTWARE METHODOLOGY

The focus of the tool is to provide means of assessment of voltage flicker, for a diverse range of load scenarios. It was imperative, however, that the complexity of such calculations is moved away from the user, to minimise misuse of the tool, and so as to maximise user acceptance. Achieving this required some modelling simplifications, and the development of a user-friendly interface. It was also critical for user support to exist in the form of 'HELP files within the tool, and an accompanying user manual. Where possible, the tool was based on existing programs to minimise user rejection and confusion.

5.3. SOFTWARE TOOL STRUCTURE

The constructed tool is comprised of several active sheets, with three of these being specifically allocated for each stage of AS61000.3.7 assessment. Another sheet is defined for the entry of load data, broken into the different categories discussed earlier. An introductory sheet and another sheet to sum multiple flicker severities were also added to complete the package. Data sheets, containing substation and conductor data, are included at the back of the tool; these sheets can easily be updated by the user as the network parameters change.

The order in which these sheets are presented is as follows:
- Introductory Sheet
- Load Definition Sheet
- Stage 1 Assessment Sheet
- Stage 2 Assessment Sheet
- Stage 3 Assessment Sheet
- Multiple Load Summation Sheet
- Substation and Conductor Data sheets

All required network parameters have been incorporated into the 'Stage 1' sheet, as this stage requires little additional information before providing assessment. The process defined by the standards Appendix A, for the prediction of flicker severity and all accompanying graphs have been incorporated into the 'Stage 2' assessment sheet, as this is where this data is utilised. As

3

Stage 3 assessment is largely theoretical, this sheet contains mainly recommendations for further investigations. Each sheet contains cells and drop-down boxes to enter data into.

The user can move between sheets/stages by simply clicking on the appropriate tab at the bottom of the workbook and entering the relevant data. Each sheet contains a 'SOLVE' button, which will perform calculations of key parameters, and assess the load. Output outcomes are displayed on a specific 'Output Results' form, containing parameters of relevance to the assessment, and which can be printed for inclusion within planning reports.

Each of the sheets has a similar format, and the tool has been given the name 'FA61000' to stand for Flicker Assessment under AS61000. Each sheet has a 'HELP' file, which can be accessed by clicking on the button in the sheets border.

5.4. USER MANUAL

To simplify usage of the tool, and in an attempt to maximise its industry acceptance, a detailed user manual was constructed to accompany the tool. Information about the usage and rationale of each of the active sheets is included in the manual, along with several worked examples, intended to clarify the tool operations. A review of the AS61000.3.7 standard is also contained in an Appendix at the back of the document to introduce novice users to this assessment process. This manual is a stand-alone document to be distributed with the tool, and is hoped to improve acceptance of both the standard and tool within the industry.

5.5. SIMPLIFICATIONS AND ASSUMPTIONS

In the tool, assumptions were made in regard to the modelling of the loads and network. It is assumed that load is fed by a single feeder, and that when constructing the equivalent electrical network, there is no other devices or impedances along the feeder between the substation and the load PCC. These assumptions have been listed both in the tool, and the user manual, so that mentioned scenarios will receive special investigation.

5.6. TESTING AND ANALYSIS

This study did not aim to extensively test the constructed tool. Testing was designed to highlight any process or computational errors. However, it was made difficult by the shortage of previously tested softwares and worked examples to benchmark the results. Further testing of the tool by Ergon Energy Corporation has been negotiated.

5.6.1. TESTING OF COMPLEX LOAD SCENARIOS

Testing of 'Complex Load' scenarios was performed using examples from the standard Appendix D. In particular example D1 was used, as assessment of this load was documented in [1] and [4]. Results from the tool in this example proved consistent with both documents; this load was easy and quick to assess using the tool. Examples D3 and D4 of the standard Appendix

A were also tested, but the lack of certain data in these examples meant that they could not be relied upon for accurate verification of the tool results because of the inevitable assumptions made. The testing of Example D1 was included in the user manual, to demonstrate the usage and validity of the tool.

5.6.2. TESTING OF INDUCTION MOTORS

Testing of induction motors proved more challenging than complex loads, as the way in which the standard has defined the assessment of induction motor starting leads to some confusion. Appendix A of the standard defines the formula below:

$$d = \frac{\Delta U_Y}{U_{NY}} = \frac{\Delta U}{U_N} \approx \frac{\Delta S_i}{S_{sc}} \quad (1)$$

Where:

d = Relative voltage change

ΔU_Y = Change in load phase-to-neutral voltage

U_{NY} = System phase-to-neutral voltage

ΔU = Change in load line-to-line voltage

U_N = System line-to-line voltage

ΔS_i = Individual load apparent power fluctuation

S_{SC} = System Short Circuit Capacity

From equation (1) it appears that the level of voltage fluctuation at the load PCC is the same as $\Delta S/S_{sc}$ ratio at the load PCC, but tests using this formula sometimes gave system voltage fluctuations well in excess of 100%. It was initially believed that this was a computational error, but review of the tool, and comparison of both ΔS and S_{sc} values against load-flow software yielded the same values for these parameters. It was surmised that there were three possible reasons for this error.

- That the value of S_{sc} was not to be calculated at the PCC, but at another point in the network;

- That the value of ΔS was not equivalent to the apparent power of the induction motor on start, but another part of its fluctuating component;

- That the ratio $\Delta S/S_{sc}$ is not related to the system voltage fluctuation as described.

Regardless of the reason, another approach was required. A modified calculation method was chosen to be implemented for use in the tool. Instead of Equation (1) from Appendix A, Equation (2) from Appendix D of the standard, as follows, was used to calculate voltage flicker on the system caused by induction motor starting.

$$d = (\frac{\Delta S}{S_{3\,phase}})[R_{System\%} \cdot \cos(\theta) + X_{System\%} \cdot \sin(\theta)] \quad (2)$$

Where $\theta = \cos^{-1}(PF_{STARTING})$.

Results from the tool using this formula, in the examples performed, were reasonable when compared against

simulated values obtained from the DINIS Loadflow package, which is normally used for MV and HV flicker studies throughout Ergon Energy. While the reason behind the discrepancy in the standard is still uncertain, Equation 2 appeared to be appropriate for the assessment of flicker during the start-up of induction motors. Thus, this formula was utilised in the tool.

As an example, a 100hp 11kv induction motor load, operating once per day, with a starting power factor of 0.3, running power factor of 0.9 and an efficiency of 95%, starting 'Direct On Line' (DOL), was assessed using the tool. It was assumed that the load was fed by the Calliope Zone substation via a feeder constructed of 20 kilometres of 7/0.104 HDBC conductors. Since the load voltage level was 11kV, the tool was set to perform an MV assessment and the relevant data was put in.

As the outcome of stage 1 assessment, it was observed that the system fluctuation was approximately 4.4%. Thus, the load failed a simple Stage 1 assessment. It was, therefore, necessary to assess the load under stage 2 of the standard. Additional data about the load characteristics, consumer capacity and network capacity was required for this stage. A consumer capacity of 600kVA and a system capacity of 6MVA were assumed. An induction motor voltage change has a relatively rectangular shape, so a rectangular periodic voltage waveshape was selected for the load. The smallest value of voltage changes per minute given was 60, so this value and a shape factor of 0.95 was obtained from the relevant graph. All these data were entered in the relevant cells and drop-down boxes appeared in various windows (corresponding to the Excel sheets) once the tool was executed. Only one window of the tool is shown in Figure 6 for demonstration.
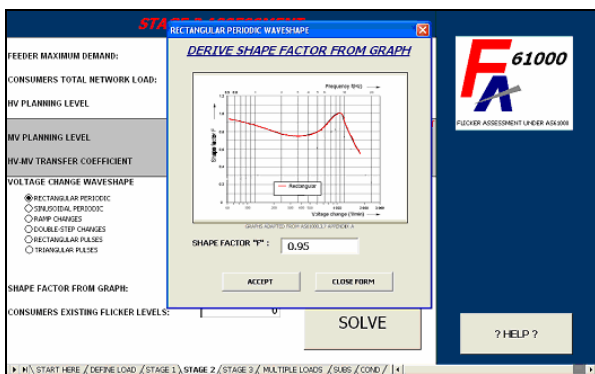

Figure 6- One of the windows of the software tool, used to enter the load data

By running the tool, it was seen that the load passed the stage 2 assessment. Thus, its flicker emission is acceptable and the motor can be connected to the network without further investigation. The results sheet for this example appears as follows.
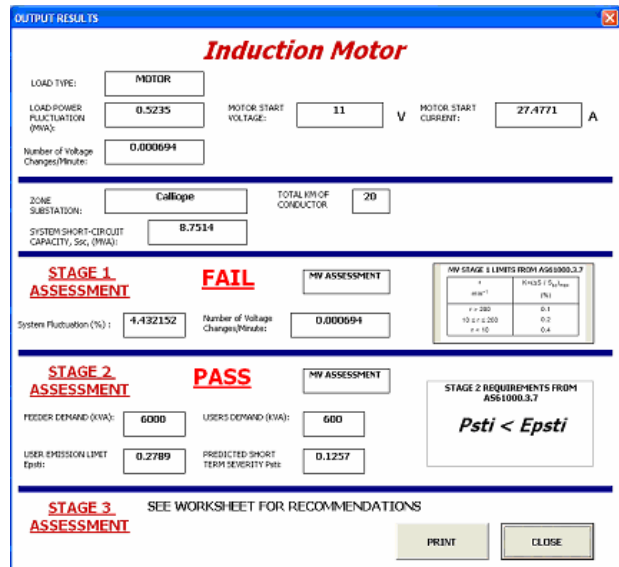

Figure 7-"FA61000 Output Results Sheet for Induction Motor Example"

5.7. INDUSTRY INVOLVEMENT

Staff at Ergon Energy, were consulted during each phase of the program development and review, to ensure alignment of the final tool with industry requirements and expectations. This involvement was important in maximising the chance of industry acceptance. The staff members of Ergon Energy had significant input into the development of the software tool.

6. ANALYSIS OF SOFTWARE TOOL

Upon initiation of the study, several key objectives were defined for the tool. These objectives defined the project, and were reviewed as the tool was developed. Evaluation of the tool against these objectives and feedback from the power utility industry application will ensure the success of this work.

The tool is hoped to be successful in its ability to assess fluctuating loads under the AS61000.3.7 standard. It is expected that it will produce reasonable results and it will facilitate the usage of the standard assessment process closely. The tool has been designed to be capable of assessing a large range of loads and load types. Any fluctuating network load can be defined as a 'Complex Load' and can be assessed if the relevant operational data is known. Use of the simplified prediction method from the standard also helps achieve this goal. Output results are in a clear and printable form and can easily be included within planning reports.

It has always been a goal to ensure that the tool is as user friendly as possible. This has been achieved through the use of preset values were possible, a VBA user–friendly interface and through the assistance of 'HELP' menus and the accompanying user manual. Close interaction with the industry staff helped developing a tool appropriate for practical applications.

The user manual has been created as a stand-alone document, to accompany the implementation of the tool within the industry. It also contains summary of the

AS61000.3.7 standard as an Appendix at the back of the manual. Much effort was devoted to both the construction of this manual and to ensure that the tool was adequate for use within industry. It is hoped that the tool and its user manual will improve both industry application and acceptance of the standard; indications thus far look promising.

7. RECOMMENDED IMPROVEMENTS

Several improvements for the tool have been outlined and are listed below.

- That the tool undertake extensive industry testing for all different load types before its release;

- That a LV package, similar to FA61000, be defined using some of the work performed for this tool and implement the AS61000.3.5 standard;

- That work be undertaken to include Single Wire Earth Return (SWER) loads into the FA61000 tool;

- That research be undertaken into the investigation of voltage-change waveforms for complex load groups to establish common assessment models for these loads.

8. CONCLUSIONS

A software tool has been developed, which provides the assessment of voltage flicker emission of fluctuating loads under the AS61000.3.7 standard. This tool has successfully met all defined objectives. The tool and its comprehensive user manual are expected to improve industry application and acceptance of the standard.

9. ACKNOWLEDGEMENT

10. REFERENCES

[1] AS/NZS61000.3.7 Standard, Electromagnetic Compatibility (EMC) – Part 3.7: Limits- "Assessment of emission limits for fluctuating loads in MV and HV power systems", 2001, Standards Australia and New Zealand.

[2] IEC 61000.3.7 Standard, Electromagnetic Compatability (EMC) – Part 3.7: Limits- "Assessment of emission limits for fluctuating loads in MV and HV power systems", 1996, International Electro-Technical Commission.

[3] Bergeron, R., Blooming, T., Burch, R., Conrad, L., Key, T., & Mark Halpin, S., "Voltage and Lamp Flicker Issues: Should the IEEE Adopt the IEC Approach?", IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 18, NO. 3, JULY 2003, pp 1088-1097.

[4] Standards Australia International, *HB264 –2003 POWER QUALITY*, "Recommendations for the application of AS/NZS 61000.3.6 and AS/NZS 610003.7", Standards Australia International, 2003.