WAVEFORM GENERATOR FOR LOAD SUSCEPTIBILITY TESTING

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Abstract:

Power quality test facilities developed at the University of Wollongong include a 10kVA waveform generator (WG) of which the detailed design and operation has been described previously. The WG is essentially a programmable IGBT voltage source inverter controlled by a micro-controller. The original intention of this generator was to test electrical equipment under the influence of harmonic distortion. This paper describes the work undertaken in further development of the WG operation to produce controlled voltage unbalance, sags and swells, and fluctuations.

1. INTRODUCTION

With the increase in the use of devices and systems that are susceptible to power quality problems there is a growing interest in equipment susceptibility and application of various mitigation techniques to ensure reliable operation. Power quality problems such as voltage sags can have an immediate impact on the operation of systems such as variable speed drives by tripping whereas the effects of voltage unbalance and waveform distortion may be felt only after a considerable period of operation of the equipment. The level of susceptibility of equipment to various types of power quality problems is often not known or not clearly specified and there is a continuous need for greater understanding, and development of test equipment and relevant standards.

Over the past five years the University of Wollongong has been developing a load susceptibility test facility in their Power Quality Centre, for load and power quality instrument testing. Being a programmable source it is possible for the 10kVA WG to produce any combination of balanced non-triplen odd harmonics up to the 20th providing that the instantaneous peak voltage is no more than 140% nominal, or above the available DC bus voltage. With other power quality disturbances such as voltage unbalance, sags and swells, and fluctuations also being a concern, it was proposed to upgrade the functions of the WG.

2. THE WAVEFORM GENERATOR

The WG consists of four components as shown in Figure 1. The primary component is a PWM IGBT three-phase voltage source inverter with a switching frequency of 10kHz [1]. The DC bus for the inverter is derived from a 30kVA auto-transformer giving a rectified DC bus voltage of approximately 800VDC. The rated output current of the PWM inverter is 28A RMS continuous and 120A instantaneous peak [2].

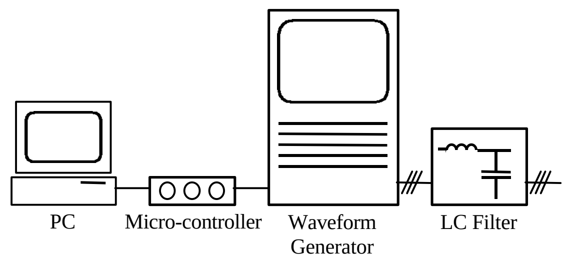

Figure 1: Layout of Waveform Generator Facility [1]

The output of the PWM inverter is passed through a second order low pass LC filter to remove the higher order switching transients. The cut off frequency of the output filter is approximately 2kHz. Some higher order frequencies arising from the inverter switching remain in the output due to the non-ideal nature of the LC filter but these do not have a significant effect on equipment being tested.

The control of the PWM inverter consists of two levels. The first level is a PC that acts as the user interface. The user interface software allows the user to enter the specifications for the desired power quality disturbance and visualise the WG output before operation. Calculation of the required IGBT switching instances to achieve the requested voltage waveforms is also performed by the user interface software. The source code for the user interface is written in C++ programming language.

The user interface is also designed to ensure that the requested output voltage waveforms do not exceed the capabilities of the WG. This is achieved by limiting the values entered by the user, ensuring the DC bus voltage is not exceeded and confirming that IGBT snubber circuit reset times are sufficient.

The second level of control is the real time switching of the IGBTs, which is managed by an Intel 87C196KC micro-controller. The switching instances for the IGBTs are pre-calculated by the user interface program and downloaded to the static RAM of the micro-controller via a serial link prior to operation. The micro-controller software utilises a series of loops and interrupts to control the IGBT switching and the overall operation of the PWM inverter.

The modulation strategy used to calculate the IGBT switching instances is based on a combination of duty cycle and the space vector PWM switching scheme. Further details of the PWM switching scheme can be found in [2].

3. SIMULATION

In the development process MATLAB was used as a simulation tool to test the application of new programs and to ensure the safe operation of the WG. Simulations in MATLAB also allowed calculation techniques to be easily transferred into C++ programming language for implementation in the user interface program.

Using MATLAB the switching instances of the IGBTs and the filtered output of the WG were all able to be calculated accurately allowing the effects of changes in modulation strategies to be studied effectively while ensuring component capabilities of the WG and the output filter are not exceeded. Such simulations found that the main limiting factor of the WG control scheme was the timing resolution of the micro-controller which at present is 1.3µs. It is intended to upgrade to a faster DSP type controller at a later stage.

PSCAD/EMTDC was also used as a simulation tool [3]. The use of PSCAD/EMTDC allowed the performance of the WG to be analysed when various types of loads are connected as output. This was a useful tool when testing the effects of having single-phase loads connected, noting that the WG modulation strategy is based on three-phase techniques. Simulations have shown that connection of a single-phase load across two of the WG output lines produces a slight increase in the level of 3rd harmonic in the output voltage waveform while still remaining well within limitations set by AS 2279.2-1991 [4].

4. VOLTAGE UNBALANCE

With the WG able to produce balanced three-phase voltages with non-triplen harmonics up to the 20th harmonic, the next desired feature was to produce both distorted and undistorted unbalanced three-phase voltage waveforms.

The WG has no output neutral connection so the output can only be regarded in terms of line-to-line voltages. This applies the limitation that no zero sequence can exist in the WG output. Thus for the production of unbalanced three-phase voltages it was important to ensure user references contained no zero sequence, as this would cause a discrepancy between the desired and actual outputs.

The user interface software was designed to only allow the user control of the magnitude of each of the three-phase voltages (eg. 415V, 410V, 405V). The corresponding phasor angles required to produce only positive and negative sequence components are calculated by the software using the cosine rule with the voltage V_{ab} always set to a phasor angle of zero as a reference. This method ensured no zero sequence was requested.

The user interface software also calculates the respective unbalance factor for the reference three-phase voltages. There are two definitions of the unbalance factor, one adopted by IEEE and the other by IEC. The definitions adopted by IEEE and IEC are expressed mathematically by equation (1) and (2) respectively.

$$u_{n(IEEE)} = \frac{max\ deviation\ \ from\ average\ \ voltage}{\frac{1}{3}(V_{an} + V_{bn} + V_{cn})} \quad (1)$$

$$u_{n(IEC)} = \frac{V_-}{V_+} \quad (2)$$

where V_- = negative sequence component
V_+ = positive sequence component

With the waveform generator capable of producing controlled unbalanced voltages, various types of equipment could be tested against different unbalance factors to determine performance tolerances. One particular operation where unbalanced testing is important is the de-rating of induction machines.

With such tests the unbalance factor is plotted against the de-rating of the machine. To complete such tests efficiently it is important that a user can enter the desired unbalance factor rather than having to calculate the required three phase voltage magnitudes. For this reason the user interface software was modified to allow the IEC unbalance factor, u_n, to be entered as the reference (along with the nominal voltage magnitude, V_{nom}). The software, using equations (3) to (6), completes calculation of the required three-phase voltage magnitudes [5].

$$\Delta = \frac{\sqrt{-6(u_n^4 + u_n^2 + 1) + 3(u_n^2 + 1)\sqrt{4u_n^4 + u_n^2 + 4}}}{(1 - u_n^2)} \quad (3)$$

$$V_{ab} = V_{nom} \quad (4)$$

$$V_{bc} = (1 + \Delta)V_{nom} \quad (5)$$

$$V_{ca} = (1 - \Delta)V_{nom} \quad (6)$$

Distorted unbalanced three-phase voltages could also be produced with triplen harmonics available due to the unbalance. The harmonics are entered as a percentage of the fundamental and given the same phase as the fundamental to ensure zero sequence is not introduced into the reference. An example of the fundamental and harmonic phasor diagrams is shown in figure 2.

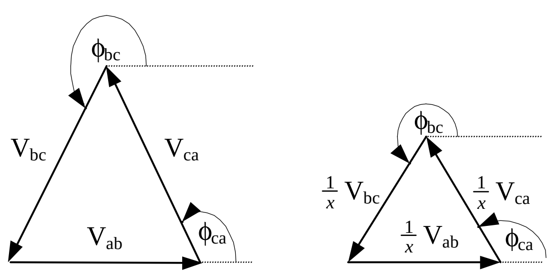

Figure 2: Phasor triangles of unbalanced system with harmonic at fraction $\frac{1}{x}$ of fundamental

With the modifications to the user interface software the WG was able to produce three-phase voltage waveforms with an unbalance factor (negative to positive sequence ratio) up to 100%. The voltage unbalance can be user specified by entering the three voltages or by specifying a given unbalance factor. As with previous versions of the user interface software the simulated outputs can be viewed prior to the application of the unbalanced voltages to the load.

Measurements of the WG output show that there is an unbalance of approximately 0.5% when a balanced output is requested. However when an unbalanced output is requested the error reduces to within ±0.05%. Examples of the WG output producing unbalanced voltages are illustrated in figure 3 and figure 4.

5. VOLTAGE SAGS/SWELLS

The philosophy of producing a voltage sag was that there would be two voltage waveforms, one at the initial voltage level and one at the sag voltage level.

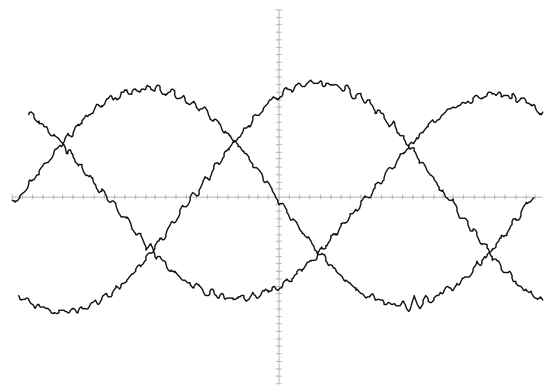

Figure 3: 415V unbalanced voltage with an IEC unbalance factor of 6%

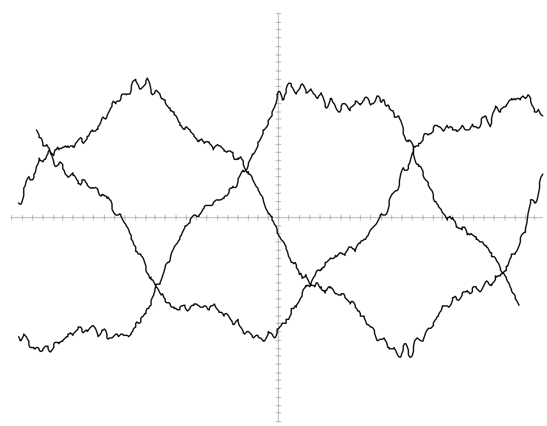

Figure 4: 415V unbalanced voltage with IEC unbalance factor of 8% and 5^{th} harmonic at 12%

This would be achieved by using two separate sets of IGBT switching sequences. The first set would produce the initial voltage waveforms and the second the sag voltage waveforms. It was necessary to store both sets before operation as the micro-controller was not fast enough for real-time down-loading from the PC.

The micro-controller program was modified to include the second set of IGBT switching sequences and other modifications to allow the transfer between the two sets of IGBT switching patterns.

Balanced three-phase sags of Type I in figure 5, can easily be specified in per unit terms with an additional phase jump, if required. For unbalanced three-phase sags however specification becomes more difficult. One method of characterising three-phase unbalanced voltage sags is presented in [6]. The most common unbalanced sags found in power systems by [6] derived from line-to-line and single-line-to-ground faults, Types II and III respectively in figure 5.

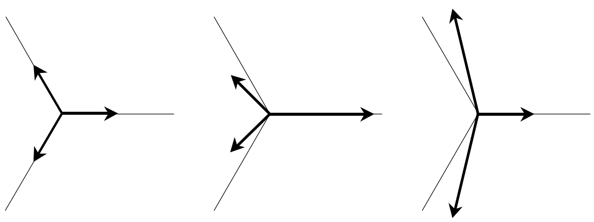

Figure 5: Phasor diagram of unbalanced voltage sags.

[6] Shows that unbalanced three-phase voltage sags of Type II or Type III can be represented by a Remaining Complex Voltage (RCV) and a Positive-Negative Factor (PNF). The RCV and PNF comprise of the vector addition (V_Σ) and vector subtraction (V_Δ) of the voltage waveform positive and negative sequence components. Using this method any unbalanced three-phase voltage sag containing no zero sequence can be specified by the terms RCV and PNF.

$$V_\Sigma = V_+ + V_- \quad (7)$$

$$V_\Delta = V_+ - V_- \quad (8)$$

The WG utilizes the method from [6] to specify the required unbalanced voltage sag. For balanced sags the WG generator also accepts sags specified in per unit. The duration of the sag is entered as the number of cycles and can range from a single cycle up to 32000 cycles (approximately 10 mins).

The software controlling the WG has been developed such that normal steady state voltages are first applied to the equipment under test and a voltage sag of given specifications is initiated from the keyboard of the PC connected to the micro-controller. The voltage sag is achieved by changing to the second set of IGBT switching patterns for the required number of cycles.

A half cycle or full cycle transition from nominal voltage to sag voltage can be produced by the WG instead of an instantaneous collapse, if required. This is achieved by selecting a third set of IGBT switching patterns during the transition period. Three sets of IGBT switching patterns is the existing limit of the WG due to the available micro-controller memory.

Figure 6 shows the WG output when a balanced sag is initiated with a ½ cycle transition time. If required, sags producing instantaneous collapse of voltage can also be produced by the WG. Figure 7 shows the WG output for an unbalanced sag of Type II with instantaneous voltage collapse.

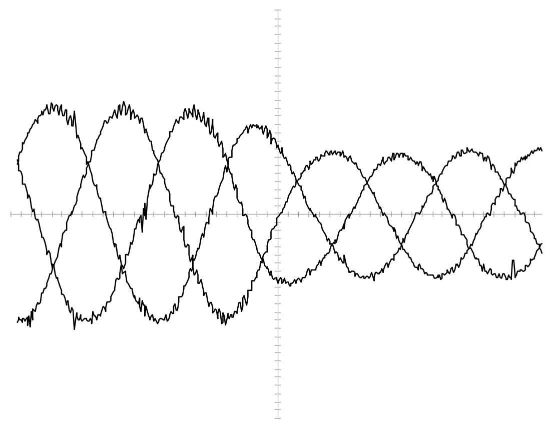

Figure 6: 415V 60% voltage sag with ½ cycle (10ms) transition time.

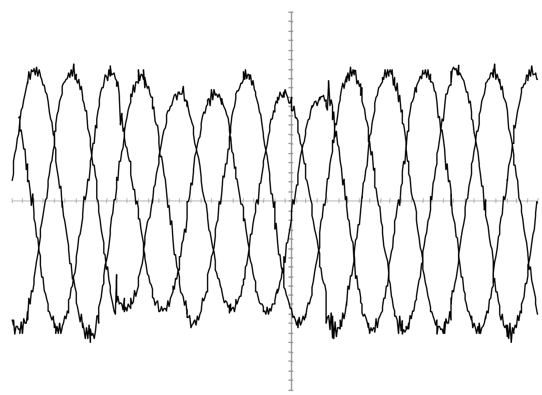

Figure 7: 415V unbalanced voltage sag (2 cycles) with RCV=0.8∠0° and PNF=1.0∠0°

6. VOLTAGE FLUCTUATIONS

The implementation of voltage fluctuations was quite simple using a slightly modified sag/swell program. Continuously toggling the control between normal and sag switching patterns for the IGBTs at a selected rate produces voltage fluctuations. Counting the number of waveform cycles and alternating between the two sets of IGBT switching patterns controls the frequency of voltage fluctuations. The operating limitations for voltage fluctuations are the same as for voltage sag and swells.

Voltage fluctuations using square wave modulation are the only type of fluctuations available, as sinusoidal fluctuations would require different IGBT switching patterns for each cycle. An example of the WG output for voltage fluctuations is shown below in Figure 8.

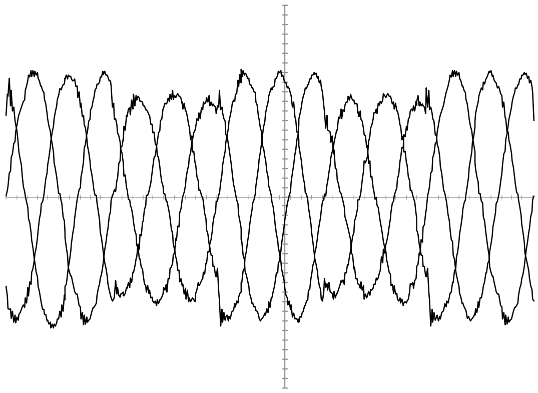

Figure 8: Voltage fluctuations produced by WG.

7. CONCLUSION

The WG is essentially very flexible in that it can potentially be used for a variety of applications. Programming of the user interface and micro-controller is quite simple and modifications for particular applications of the WG are usually easy to achieve.

The production of voltage unbalance, sags and swells by the WG were evaluated under load to ensure the expected operation and voltage fluctuation immunity tests were carried out on several pieces equipment where satisfactory results were obtained.

The upgrade to the WG provides the University of Wollongong's Power Quality Centre with a load testing facility that can perform immunity tests, harmonic losses measurement and power quality monitoring device calibration.

8. REFERENCES

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