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Sag testing of dairy farm milking equipment

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Sags are widely reported as being one of the worst power quality problems and are particularly common in rural areas. Automated milking equipment on dairy farms are thus very susceptible to malfunction by sags. In assessing the relative cost/benefits of sag mitigation in the dairy or the supply network it is important to know the dairy equipment immunity level. It is shown how a harmonic generator can be used to determine this information. Testing revealed that the motor contactor was a critical component as it was unable to ride through a 40% sag longer than about 0.5 seconds. The milking equipment without contactor gave unsatisfactory performance for 50% sags longer than 1 second and for interruptions exceeding 0.5 second.

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Sag testing of dairy farm milking equipment

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Abstract: Sags are widely reported as being one of the worst power quality problems and are particularly common in rural areas. Automated milking equipment on dairy farms are thus very susceptible to malfunction by sags. In assessing the relative cost/benefits of sag mitigation in the dairy or the supply network it is important to know the dairy equipment immunity level. It is shown how a harmonic generator can be used to determine this information. Testing revealed that the motor contactor was a critical component as it was unable to ride through a 40% sag longer than about 0.5 seconds. The milking equipment without contactor gave unsatisfactory performance for 50% sags longer than 1 second and for interruptions exceeding 0.5 second.

Keywords: power quality, sag, equipment immunity, CBEMA curve

I. INTRODUCTION

Sags are defined by IEEE Std 1159-1995 [1] as a reduction in rms voltage to the range 10-90% for a time of less than 1 minute. They are reported as being one of the major power quality problems, especially in rural areas. A single phase sag with a rectangular envelope can be characterised by magnitude and duration and there is work at present to extend this idea to three phase sags with more complex waveforms.

When a process is critical, it is useful to know the sag capability of the equipment to allow cost-effective sag mitigation precautions to be taken for a given site. In the past, the sag capability of some computers has been given by the CBEMA curve [2], and recently by the ITI curve on a plot of sag magnitude versus duration, but it has not been established if other equipment can be treated in the same way. One of the present problems in the management of power quality is manufacturers' lack of knowledge of both the level of sag disturbances on the power system and the sag immunity level of critical equipment. It is rare for equipment to be known in sufficient detail for the sag capability to be determined from simulation studies and sag testing is necessary to determine the real capability of the equipment.

There are at present no standard approaches to hardware set-up for testing equipment for sag immunity. The IEC international standard on sag immunity [3] discusses the types of sags which equipment should be able to withstand and has appendices on sag generation, briefly mentioning an electronic tap-changer and a waveform generator with power amplifier. The first sag generator is very restricted in the types of sag waveforms which can be generated. The second has no such restrictions in principle but appropriate power amplifiers are only just beginning to be available as off-the-shelf items and are very expensive for even modest power levels in the 10-20kVA range. At low powers, a linear amplifier and step-up transformer combination can be used as described in [4] for testing ac contactors. [5] describes the use of a synchronous generator with the field current controlled to give an appropriate voltage envelope. This solution can in principle be scaled to very high powers but is expensive, heavy and only able to produce balanced sags. The generator needs to be under-utilised to avoid impedance effects. [6] emphasises the importance of the correct representation of mechanical load in testing the sag capability of motors and drives and describes a dynamic dynamometer which can act as a synthetic mechanical load where the equations of load dynamics are known accurately.

The present study arose out of a problem with milking equipment at dairy farms. Each cow has 4 cups attached by suction from a vacuum reservoir, evacuated by a single phase induction motor driving a pump. Dairy farms are of course situated in rural areas and can be highly exposed to sags. It has been found that even brief sags can cause loss of vacuum and the detachment of all cups. The time to restart the vacuum equipment and connect up all the cups can be many times longer than the sag duration and be very inconvenient. There was strong interest from both the supplier of the equipment and the local distributor in identifying the weak link in the vacuum system with a view to developing a cost-effective improvement in the sag immunity.

The University of Wollongong had developed a power electronic solution for the testing of equipment harmonic immunity [7] and realised that the basic hardware would also be able to generate a wide variety of sag waveforms. This paper will describe the control software changes that were made to allow sag generation and the result of testing the dairy farm vacuum equipment to experimentally determine the equipment's critical parts and to allow improvement of its sag response.

II. WAVEFORM GENERATOR (WG)

The WG consists of four components as shown in Fig 1. The primary component is a PWM IGBT three-phase voltage source inverter with a switching frequency of 10kHz [7]. The DC bus for the inverter is derived from a 20kVA transformer giving a rectified DC bus voltage of approximately 800VDC. This allows it to generate waveforms with crest values of up to 40% greater than a nominal 415V line-to-line waveform containing disturbances with a bandwidth to about 1 kHz. The rated output current of

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the PWM inverter is 28A RMS continuous and 120A instantaneous peak [8] limited by the voltage produced at turn-off by the IGBT snubber network.

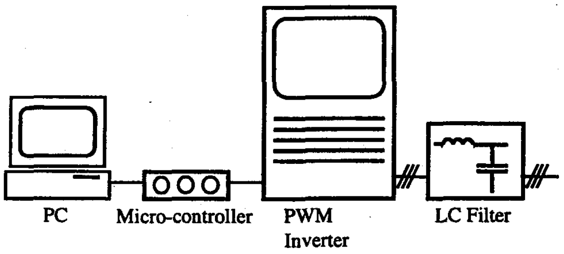


Fig. 1. Schematic of Waveform Generator

A second order low pass LC filter is placed at the output of the PWM inverter 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.

There are two levels to the control of the PWM inverter. 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 source code also ensures 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 real time switching of the IGBTs is the second level of control 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 inverter switching strategy has been chosen to make best use of the inverter switching frequency and to give consistent pulse polarity in the case of a normal waveform. 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. The details of the modulation strategy are described in [8] and are based on the following concepts.

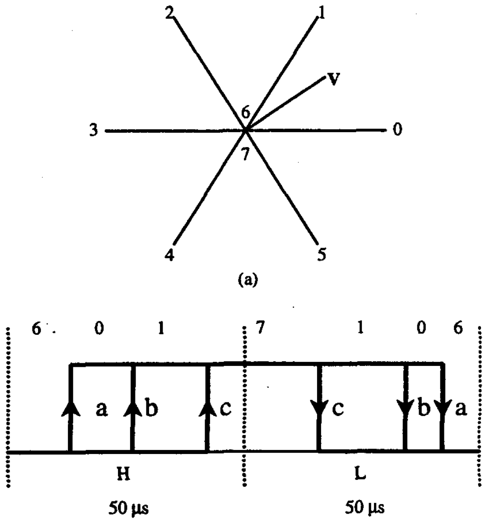
(i) The eight possible inverter switching states gives three phase voltages which can be represented by seven distinct vectors (output voltage in $\alpha\beta$ co-ordinates - Fig. 2(a))

(ii) One supply cycle can be divided into 200 distinct switching periods, each of length 100μs.

(iii) For each half switching period, the required time-varying vector is approximated by its value at the midpoint of the interval. It can be shown that this vector can be synthesised by an appropriate mix of the vector on either side and the zero vector numbers 0, 1 and one of the zero-voltage vectors 6 and 7.

(iv) The switching loss in the IGBTs are minimised by applying an order that involves each leg sequentially switching high in the first half period and low in the second half period similar to the pattern shown in Fig.2(b).

(v) An interval of at least 5μs is placed at the end of each switching period to allow the appropriate snubber to reset.



(a)

(b)

Fig. 2(a). Reference vector V. (b). Switching sequence over one interval involving vectors 6. 0, 1 and 7. The corresponding inverter vectors are labelled at the top.

In the case of sag testing of a single phase induction motor (and auxiliary devices) there are some special problems which do not arise in other sag testing (eg of three phase inverters or small single phase power supplies).

1. A large single phase load draws a larger and lower frequency ripple current from the input rectifier with corresponding higher duty on the rectifier capacitor.
2. The motor current upon sag recovery is high, comparable to DOL values, reaching the instantaneous current limit of the supply inverter.

It was found through simulation and experimental results that the 3rd harmonic voltage was less than 1.5% of the nominal output voltage, a level considered satisfactory for the testing of the dairy equipment.

III. VOLTAGE SAG CONTROL

Many different aspects of sags have been identified and shown to have some effect on load performance. Some of the parameters which have been suggested for characterising sags include

- Pre-fault voltage
- Point-on-wave of sag initiation
- Rate of fall of voltage on sag initiation
- Depth of sag
- Unbalance
- Duration
- Rate of rise to recovery
- Phase-jump

The testing of equipment for all combinations of these parameters would be an exhausting task. As the objective was not the standardised testing of sag immunity but the identification of weak points in design, we have decided to concentrate on Pre-fault voltage, Depth of sag and Duration. Unbalance is not an issue as the motor is single phase.

The generated waveform had four distinct periods as shown in Fig. 3.

(i) A normal section during which the equipment reached steady state
(ii) A sag period (corresponding to a fault) when the rms voltage dropped to a low value
(iii) An interruption period (corresponding to recloser operation) in which the voltage fell to zero for a few seconds
(iv) Recovery to a normal waveform.

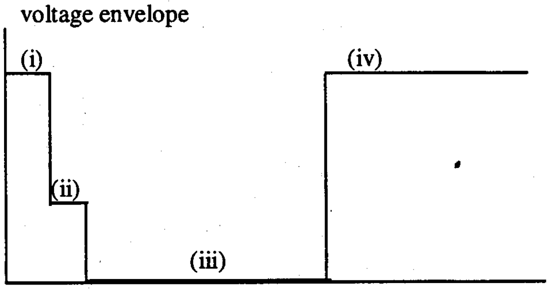


Fig. 3 Generated voltage envelope

A voltage sag can be considered as two adjoining voltage waveforms, one at the initial voltage level and one at the sag voltage level. This can be achieved by the WG 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. The micro-controller program stores both sets of IGBT switching sequences and transfers between the two sets of IGBT switching sequences. It is necessary to store both sets of IGBT switching sequences in memory before operation as the micro-controller is not fast enough for real-time down-loading from the PC. Duration can be controlled from 1 to 32000 cycles (about 10 minutes). The moment of sag initiation is determined from the PC keyboard.

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.

IV. DESCRIPTION OF EQUIPMENT AND TEST APPARATUS

The Dairy Vacuum System (DVS) is shown in Fig.4 with schematic diagram in Fig. 5. It consists of a vacuum pump with a pumping capacity of 3000 litres/min driven by a single phase 7.5 kW 4-pole 480 V single phase induction motor. These two items were mounted on a pressure vessel which had a pressure regulator that limited the minimum pressure to about 50 kPa absolute. A 480 V contactor for motor starting was initially included in the circuit to test the sag susceptibility of the type of contactor that would be used in a typical installation.

V. TEST SET-UP

The voltage sag and interruption susceptibility tests were performed using a 10 kVA WG that is able to produce voltage sags of various depths and duration. To enable the WG to be used as a single-phase voltage supply for sag testing some minor software and hardware modifications had to be completed. The tests required a normal-to-sag-to-interruption voltage sequence. Similar to the operation of producing a single sag with smooth transition, three sets of IGBT switching instances are required to produce the three level voltage sequence. Alternating between the three sets and counting the number of cycles each set is applied allows the transition to each voltage level be achieved.

The induction motor initially had a 2Ω resistor connected in series to limit the starting current of the motor to less than 120 A_{peak} which is the maximum instantaneous current of the waveform generator. This was later replaced with an inductor of 6mH as this gives a similar limit in starting current but less voltage drop for normal operation.

For the tests performed, a range of quantities were monitored. The voltage applied to the motor was recorded on a Nicolet System 200 digital oscilloscope using its differential inputs and 100X probes. Current was measured by a Pearsons Electronics Model 101 wideband current transformer and recorded on both the Nicolet oscilloscope and a LeCroy 9304AM digital oscilloscope. A digital output from the micro-controller was added for the sag testing. By switching the digital output high when a sag is initiated and low at the end of a sag all monitoring equipment was able to be triggered simultaneously. This enabled time referencing of signals on both oscilloscopes.

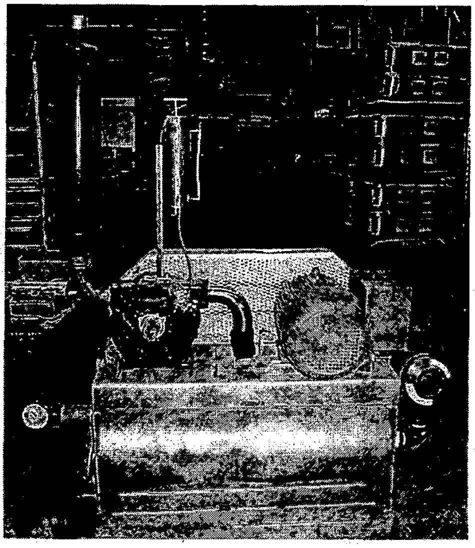


Fig. 4. Photo of vacuum motor, pump and reservoir

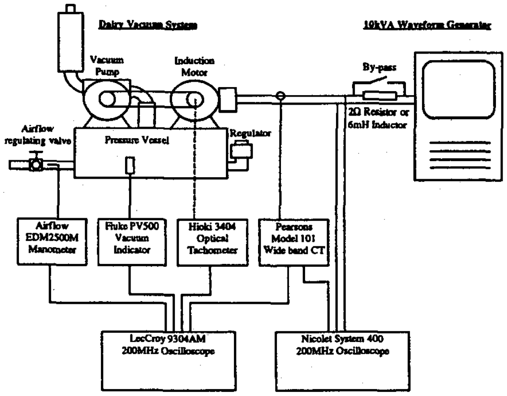


Fig. 5. Dairy vacuum system and test equipment

The LeCroy oscilloscope also recorded motor speed, pressure in the pressure vessel, and air flow into the pressure vessel. Motor speed was measured using a Hioki 3404 optical tachometer; pressure was measured with a Fluke PV500 Pressure/Vacuum indicator and air flow with an Airflow EDM2500 Electronic manometer. Air flow into the vessel was varied for different tests by means of a regulating valve to simulate various degrees of air leakage (and hence motor loading) that would occur in an actual dairy situation.

The tests were carried out in four stages:

1. Initial tests were performed on the unloaded motor including starting currents, and power factor during start up and normal operation.
2. Preliminary tests to assess the decay of vessel pressure and airflow into the vessel during a long-term interruption for initial air flows of 300-2000 litres/minute.
3. Sag tests: the motor was run up to speed then the 2Ω resistor was shorted before the sag was applied. Sags of 10-50% and duration 3 cycles to 10 seconds were applied for air flow rates of 0-1000 litres/minute. During these tests it was determined that the motor contactor was the component causing sag susceptibility. Sag tests were repeated with the contactor by-passed to test the limits of the remaining system.
4. Short interruption tests. Interruptions from 3 cycles to 3 seconds were applied for conditions of no air flow and air flow of 1000 litres/minute. A series 6mH inductor replaced the resistor for these tests to limit the motor recovery current.

VI. TEST RESULTS

A. Initial Tests

The maximum instantaneous starting current recorded was 108A. There was a significant voltage drop across the resistor during starting (as expected).

B. Preliminary Tests

The air flow rate was controlled by the opening of the pressure vessel regulating valve. The motor current for the flow rates of 300 litres/minute to 2000 litres/minute remained approximately the same at around 16A. The motor supply was disconnected to observe decay of pressure in vessel and air flow into vessel. The time for motor to reach a complete stop after disconnection of the supply varied considerably for different air flow rates. The time for the pressure in vacuum vessel to return to atmospheric slightly decreased for increasing flow rates. The air flow rates remained stable until pressure in the vessel increased to a critical level (approximately 56 cm-Hg) at which time it began to decay rapidly to zero over a period of a few seconds.

C. Voltage Sag Tests

Fig. 6 shows a typical load voltage and current trace recorded during a sag test. Initially the air flow rate was set to zero and sags of 10% to 40% were applied for various durations. Results are shown in Table 1. For increasing depth and duration of sags, motor current can be seen to increase and motor speed decrease. However, sags to a depth of 30% have little effect on vessel pressure, giving a maximum pressure rise of only 4%. A sag of 40% with a duration greater than 0.5 seconds caused the motor contactor to drop out. This suggested that the motor contactor was the item most susceptible to voltage sags.

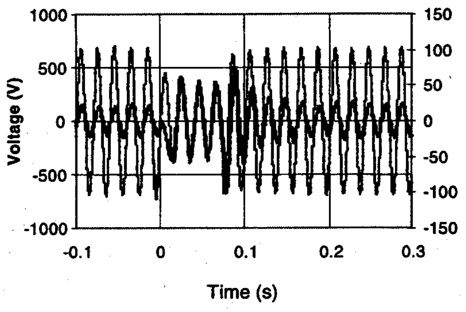


Fig. 6. Voltage (the lighter trace) and current recorded during sag test (no air flow, sag of 40% for 3 cycles)

At this stage the motor contactor was removed from the circuit. With the air flow rate still at zero the 40% sag was reapplied to establish the sag ride through performance of the rest of the system (Table 2). It was found that for sag durations of 1 second or greater the motor reverts back to the starter windings drawing excessive current. With low motor speed (83% reduction for a 3 second sag) the vessel pressure experiences a significant rise in pressure (13%) affecting the overall operation of system.

Air flow rates of 500 litres/minute and 1000 litres/minute were then introduced to the tests (Table 2). With the new air flow rates, sags of 40% were applied initially. Results were similar to the case with no air flow, with pressure rise only increasing to a maximum of 14%. For a sag with duration greater than 3 cycles, the air flow remained reasonably stable provided pressure remained below 56 cm-Hg and the motor stabilised at approximately 50% speed during the sag.

For the same air flow rates sags of 50% were then applied. A sag for 3 cycles had little effect on operation but longer duration sags caused the motor to reverted back to the starting winding due to drop in speed after approximately 0.3 seconds. Current stabilised at 65A_{peak} and pressure increased as speed decreased. Without air flow, pressure increased by approximately 50% and motor stalled after about 1.4 seconds. With air flow, pressure increased by approximately 60% and motor speed stabilised at about 17% of full speed after approximately 1.4 seconds. Air flow rate fell gradually during the 3 second sag as pressure was not low enough to stabilise airflow.

D. Short Interruption Tests

For the short interruption tests the series resistor was replaced with a 6mH inductor to protect the inverter from large motor currents on sag recovery. This gave a 16V drop in 480V under normal conditions and should not have a significant influence for the sag duration although it is somewhat larger than the impedance of a rural circuit. The Dairy Vacuum System was tested for short interruptions of varying duration firstly with air flow at zero and then at 1000 litres/minute (Table 2).

For an air flow rate of zero it was found that interruptions as small as 3 cycles cause a momentary drop in speed to 59%, that in turn produced a rise in vessel pressure by 9% for a period of approximately 0.5 seconds. Current was excessive after interruption at around 80A_{peak}. Operation returned to normal after 0.6 seconds for a 3 cycle interruption. An interruption for 0.5 seconds caused a rise in pressure of 47% and a reduction of motor speed to 12% of full speed. If the interruption was greater than 1 second, vessel pressure returned to atmospheric and the motor came to a complete halt. An air flow rate of 1000 litres/minute resulted in higher pressure rises for sags of 3 cycle and 0.5 second duration (17% and 56% respectively) but much the same results for longer sags. This suggested the system may fail for an interruption of duration 1 second or greater due to the dramatic increase in vessel pressure.

Test inputs			Test outputs		
Sag depth (%)	Sag duration	Air flow rate (L/min)	% increase above pre-sag current	% increase above operating pressure	% decrease below operating speed
10%	3 cyc	nil	-	-	-
10%	1 s	nil	1%	-	-
10%	3 s	nil	1%	-	-
20%	3 cyc	nil	-	-	-
20%	1 s	nil	5%	-	1%
20%	3 s	nil	5%	-	2%
20%	10 s	nil	5%	-	2%
30%	3 cyc	nil	28%	-	1%
30%	1 s	nil	36%	1%	3%
30%	3 s	nil	36%	4%	3%
30%	10 s	nil	36%	4%	3%
40%	3 cyc	nil	105%	2%	5%
40%	0.5 s	nil	195%	8%	45%
40%	1 s	nil		motor contactor opened	
30%	3 cyc	1000 L/min	22%	-	1%
30%	1 s	1000 L/min	36%	4%	2%
30%	3 s	1000 L/min	36%	4%	3%
30%	10 s	1000 L/min	36%	4%	3%

Note: 1. Resistor connected in series during startup but shorted out during sag testing
2. Motor pre-sag operating current was approximately 16A for all tests

Table 1: Voltage sag test results with motor contactor in service

Test inputs			Test outputs		
Sag depth (%)	Sagduration	Air flow rate (L/min)	% increase above operating current	% increase above operatingpressure	% decrease below operatingspeed
40%	3 cyc	nil	90%	-	1%
40%	1 s	nil	250%	13%	50%
40%	3 s	nil	250%	13%	83%
40%	3 cyc	500 L/min	90%	-	2%
40%	1 s	500 L/min	250%	14%	46%
40%	3 s	500 L/min	250%	14%	53%
40%	3 cyc	1000 L/min	91%	-	3%
40%	1 s	1000 L/min	250%	14%	52%
40%	3 s	1000 L/min	250%	14%	52%
50%	3 cyc	nil	127%	-	1%
50%	1 s	nil	186%	19%	77%
50%	3 s	nil	182%	51%	100%
50%	3 cyc	1000 L/min	127%	-	1%
50%	1 s	1000 L/min	186%	33%	78%
50%	3 s	1000 L/min	186%	58%	83%
100% (interruption)	3 cyc	nil	-	9%	41%
100% (interruption)	0.5 s	nil	-	47%	88%
100% (interruption)	1 s	nil	-	100%	82%
100% (interruption)	3 s	nil	-	100%	100%
100% (interruption)	3 cyc	1000 L/min	-	17%	42%
100% (interruption)	0.5 s	1000 L/min	-	56%	83%
100% (interruption)	1 s	1000 L/min	-	100%	100%
100% (interruption)	3 s	1000 L/min	-	100%	100%

Note: 1. Resistor connected in series during startup but shorted out during sag testing
2. Motor pre-sag operating current was approximately 16A for all tests
3. WG tripped on sag recovery for 50% sags (except 3 cycle sag)
4. 6mH inductor (instead of resistor) connected in series during interruption tests

Table 2: Voltage sag test results with motor contactor by-passed.

E. Relationship with ITI curve

The test conditions are shown in Fig. 7 overlayed on the ITI curve, a recent development of the CBEMA curve. Results which pass, fail or are borderline are distinguished. It can be seen that the test conditions cover a similar range of sag depth and durations. The limit of susceptibility of the equipment is slightly below and to the right of the curve. It is of interest that a curve developed for 120V/60 HZ equipment which is mainly electronic in nature appears to be applicable to this case.

VII. CONCLUSIONS

The investigation covered the use of a 10kVA harmonic generator for voltage sag testing of three phase and single phase equipment. The major limitation of the present design is the inability to carry the full motor DOL current after sag recovery. It is now planned to replace the existing IGBT modules with more modern designs allowing snubberless operation and peak current ratings of 175 Arms for several cycles.

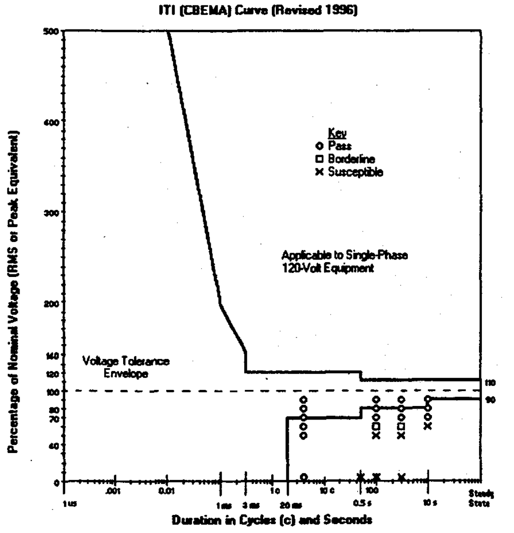


Fig. 7. Test conditions and results for equipment with contactor removed overlayed on ITI (CBEMA) curve [9]

Some detailed observations can be made of the dairy vacuum system. The motor contactor is the first 'weak link' as it will not ride through a sag of 40% for longer than 0.5-0.6 seconds whereas the other tests suggest the rest of the equipment should withstand such a sag. This finding is similar to what has been reported for several industrial processes elsewhere.

Small changes in motor speed produced by sags less than 30% do not affect the pressure or airflow. Sags of 40% cause an increase in vessel pressure but not significant enough to produce large variations in airflow suggesting that the system should withstand such sags. Sags of 50% with duration greater than one second may see the system fail as pressure rises significantly. An interruption of duration greater than 0.5 seconds would probably cause the system to fail as the pressure rises dramatically. This means the system could not withstand a distribution system circuit breaker auto re-close operation in its current design if re-close times are more than 0.5 seconds.

When plotted on a graph of voltage versus sag duration, the immunity limit of the equipment is close to the ITI curve. This reinforces the usefulness of using CBEMA or ITI curves for reporting sag events at a site. The immunity level could be improved with the provision of dc-controlled contactors and an increase in the size of the vacuum reservoir.

The problem of ensuring compatibility between equipment and the power system is one that is not yet satisfactorily addressed in this country. There needs to be industry agreement on a standard sag-testing procedure and an immunity level expressed in terms such as the ITI curve.

VIII. ACKNOWLEDGEMENTS

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