Voltage Sag Immunity Testing for Single-phase Electrical and Electronic Equipment

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***Abstract*— This paper presents a methodology for immunity assessment of electrical and electronic single-phase up to 1 kVA equipment. The design and construction of a prototype of a shunt impedance based voltage sag generator to assess the immunity level is presented. The methodology for immunity assessment was developed considering advantages and limitations of the implemented sag generator prototype. A test of immunity to voltage sags on a DC motor was carried out. Test results are presented and analyzed.**

***Index Terms*—electromagnetic compatibility, equipment immunity, power quality, sag generator, voltage sags**

I. Introduction

NOWADAYS, power quality is a topic of increasing interest due to sensitivity of modern electrical and electronic equipment of power system customers to electromagnetic interference phenomena. Voltage sags are one of the most common disturbances because their main causes are faults in power systems [1], [2], [3]. This phenomenon is a short-time reduction in rms voltage that results in failures in essential equipment in industry, which means tripping of production processes, directly affecting financial aspects [4]. Typical industrial equipment sensitive to voltage sags are computers, control process equipment such as sensors, remote terminal units and man-machine interface devices, telecommunications equipment, electrical arc lighting, adjustable speed drives, programmable logic controllers, etc. [5].

Improving immunity of equipment is a cost-effective solution to voltage sags, given that reducing the number of faults implies high investments in power systems, and finally, power system faults always exist [6], [7].

The best source of data about immunity to voltage sags is the equipment manufacturer. Although, this information is not always available; hence the user can collect data on equipment performance with an immunity test [8]. Immunity assessment of electrical and electronic equipment consists in determine magnitudes and durations of voltage sags that the equipment can ride-through without failure or interruption in a specified electromagnetic environment, this can be achieved with some degree of accuracy from tests in controlled environments [4]. For this purpose a voltage sag generator and laboratory equipment for data acquisition are required [5].

Voltage sag generators are classified in four topologies [9]: generator based, shunt impedance based, transformer based and full converter based (back-to-back converter). The shunt impedance based voltage sag generator is typically used to test low voltage ride-through in wind system converters. In these tests, voltage and current conditions at the point of connection in the power system during a fault are emulated [10]. Typically, sag generators used in wind energy systems tests are large power (up to 5 MW), as those presented in [10]-[13].

In this paper, a methodology for immunity testing is proposed, and the design and construction of a voltage sag generator to test the immunity level of single-phase electrical and electronic equipment up to 1 kVA is described. The prototype was implemented with a shunt impedance based topology because of its capability to produce similar electrical conditions to those that occur during a fault in the power system [9], [11], [14].

II. Voltage Sag Generator Analysis

The operating conditions and design features of the voltage sag generator are associated with the proposed immunity assessment methodology by the authors, and availability of components. Part of the methodology for immunity assessment is presented in [14]-[16], and some aspects are summarized as follows: voltage sags must be rectangular to evaluate the impact of magnitude and duration on the Equipment Under Test (EUT); resistors are used to implement the impedances of the topology, because of its availability and proper operation in low power applications; the prototype is designed for testing low-voltage single-phase up to 1 kVA (a high percentage of essential equipment in industry has those rated parameters, such as: PLCs, ASDs, contactors, motors, computers, etc. [4]).

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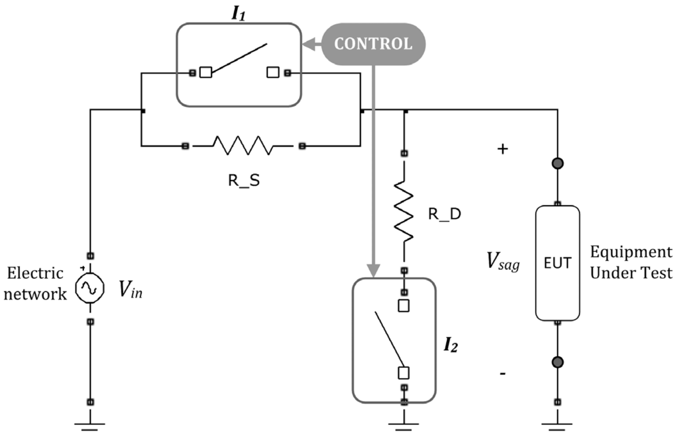

Fig. 1. Topology of the shunt impedance based voltage sag generator

Figure 1 shows the proposed shunt impedance based topology for the voltage sag generator. The prototype consists of two variable resistors (R_S and R_D), two power switches (I_1 and I_2) and a control system. Switch I_1 (bypass) is normally closed allowing the electrical network voltage on the EUT. To produce the voltage sag, switch I_1 opens and I_2 (normally open) closes. Sag magnitude is determined by the voltage divider between R_S and the parallel between R_D and the impedance of the EUT, as it is shown in (1). In case of open circuit operation, sag magnitude is determined by the divider between R_S and R_D, which is shown in (2).

$$V_{sag} = \frac{R_D \| Z_{EUT}}{R_S + (R_D \| Z_{EUT})} V_{in} \quad (1)$$

$$V_{sag} = \frac{R_D}{R_S + R_D} V_{in} \quad (2)$$

III. Prototype Design and Implementation

A. *Series Resistor (R_S) and Shunt Resistor (R_D)*

The actual resistors R_S and R_D used in the prototype are shown in Figure 2. They were built with ferronickel wire rolled on a tubular clay core. The resistor has a plaster layer which covers the rolled wire, leaving a window (A in Figure 2 (a)), which enables contact with wire for selecting a resistive value. The wire has different gauges, related to the maximum power that it must dissipate: the lower resistance, the higher current in resistors and the higher gauge of wire. In Figure 2 (a), change in wire gauge is noticed, which is higher when approaching the ring B1. Moreover, Figure 2 (a) shows a ring with a clamping system (C in figure), which allows electrical contact at different points of resistor through the window A. The implemented system for adjusting R_S and R_D resistance is presented in Figure 2 (b), it consists of electrical contacts disposed in different points of reference in the resistor between B1 and B2, which allow selecting resistive values by switches. Table I summarizes the electrical characteristics of the built series and shunt resistors and Table II shows the resistance value associated with each switch for R_S and R_D.

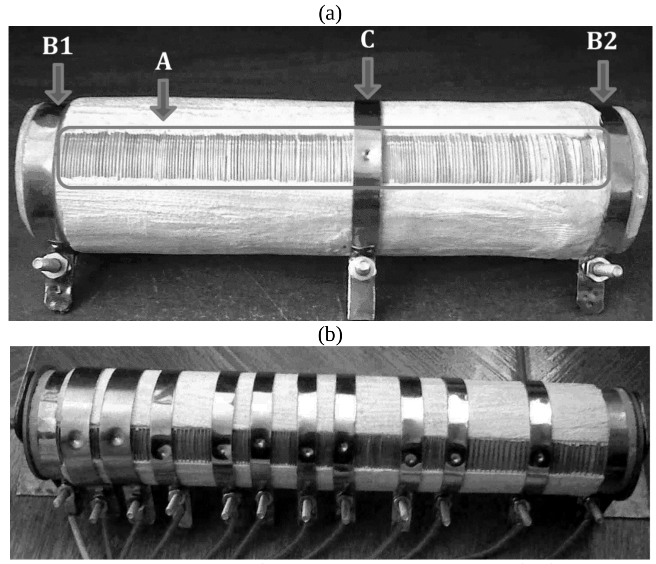

Fig. 2. (a) Description of built resistor and (b) points of reference

TABLE I. R_S AND R_D PARAMETERS

Resistor	Resistance (Ω)	P_{MAX} (W)
R_S	0 - 100	600
R_D	0 - 300	100

TABLE II. ASSOCIATED RESISTANCE TO EACH SWITCH

Switch	1	2	3	4	5	6	7	8	9	10	11
R_S (Ω)	5	10	20	30	40	50	60	70	80	95	100
R_D (Ω)	12	24	36	50	100	150	180	200	230	280	300

B. *Power switches (I_1 and I_2)*

The power switches (I_1 and I_2) were implemented with a coupling circuit and two MOSFETs in bidirectional topology, which allows fast turn-on and turn-off and current flow in both directions (AC) [9]. Opening and closing are determined by the control signal to a previous stage of optical coupling.

C. *Control system*

It consists of a microcontroller, a keyboard, a LCD and a USB communication port. The microcontroller stores the program with the operation mode of prototype, which is described in Section IV. The keyboard is the interface between user and generator, allow signing in orders while options are displayed on the LCD. The USB port is the communication channel used to send information from a PC to the microcontroller during reprogramming of the control board. The control board sends the signal to open or close switches I_1 and I_2 through the microcontroller.

D. *DC power supplies*

Two DC power supplies are used for powering the control board and coupling circuits, the first one with two outputs: 5 VDC to power the control board, and 12 VDC to power the coupling circuit to the switch I_1; and the second one with a 12 VDC output, used for the coupling circuit of switch I_2.

IV. PROTOTYPE CONSTRUCTION

Figure 3 presents the built prototype from each of the stages: series and shunt resistors, power switches, control system and DC power supplies. Each component is numbered, and corresponds to: (1) series resistor (R_S), (2) shunt resistor (R_D), (3) power switches (I_1 and I_2), (4) control system, (5) switches for resistance selection in R_S y R_D, (6) general switch, and (7) output (to EUT).

The implemented algorithms to control the prototype of voltage sag generator are based on the immunity assessment methodology for analyzing the impact of voltage sags on electrical and electronic equipment developed in this project. As a result, assessment mode of the prototype was established. It is based on the algorithm presented in Figure 4, which presents the procedure and interaction between voltage sag generator control and user to obtain the voltage tolerance curve of the EUT.

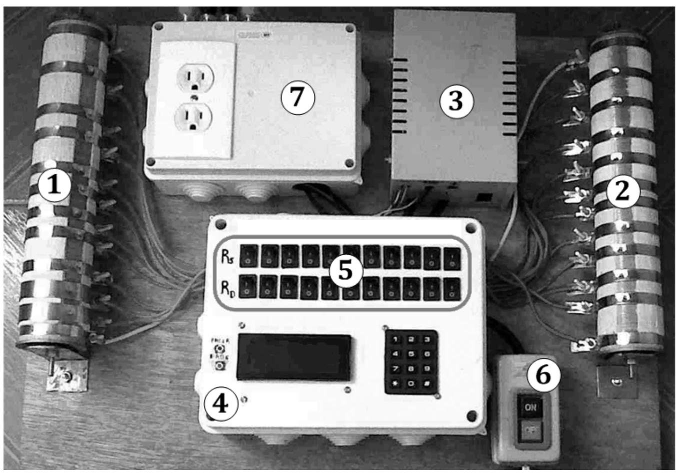

Fig. 3. Built prototype of voltage sag generator

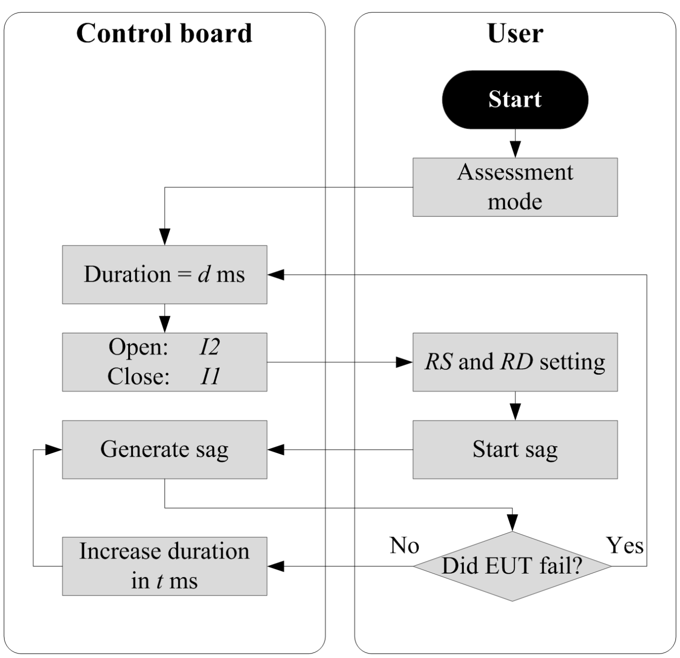

Fig. 4. Assessment mode algorithm

Before starting the test, initial duration (d ms) and incremental steps (t ms) are defined. Furthermore, the output variable of the EUT must be established, and minimum operating condition must be determined, which depends on the production process associated with the equipment [4]. Since this variable can be electrical, mechanical, etc., it should have adequate measurement equipment. Settings of sag magnitude are performed manually during testing, varying resistance of R_S and R_D. For each magnitude, the voltage sag generator automatically increases duration until it is determined that the EUT has failed. Finally, the voltage tolerance curve is obtained from information on magnitude and duration of voltage sags that causes failure in the EUT.

V. IMMUNITY TEST (DC MOTOR)

In the test, the voltage tolerance curve of a DC motor was obtained. Figure 5 shows the complete assembly, where the following elements are presented: (1) test bench (DL 1017), (2) voltage sag generator, (3) power analyzer (Fluke 435), (4) primary DC power supply, (5) DC motor (DL 1024R), (6) DC generator (DL 1024R), (7) oscilloscope (Rigol DS1102E), and (8) measurement instruments. Figure 6 presents classification and interaction of equipment for conducting the immunity test, and Figure 7 shows the electrical scheme.

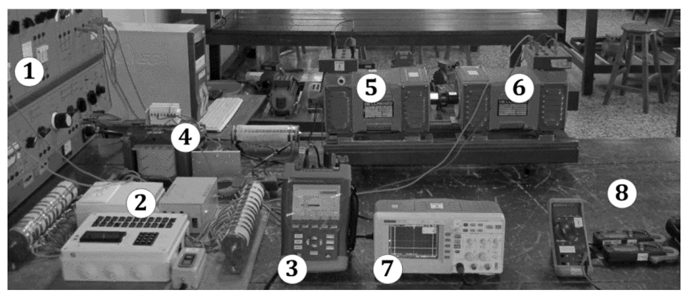

Fig. 5. Assembly of the immunity test

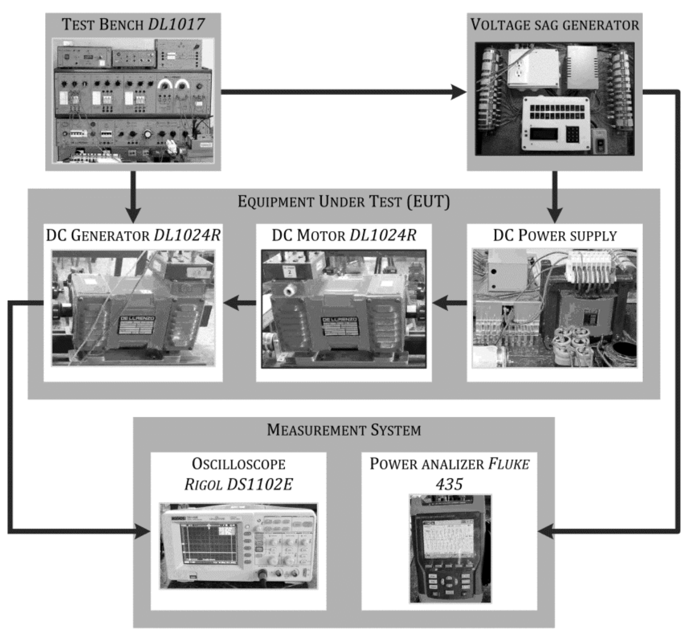

Fig. 6. Classification of equipment and scheme of connection for the immunity test

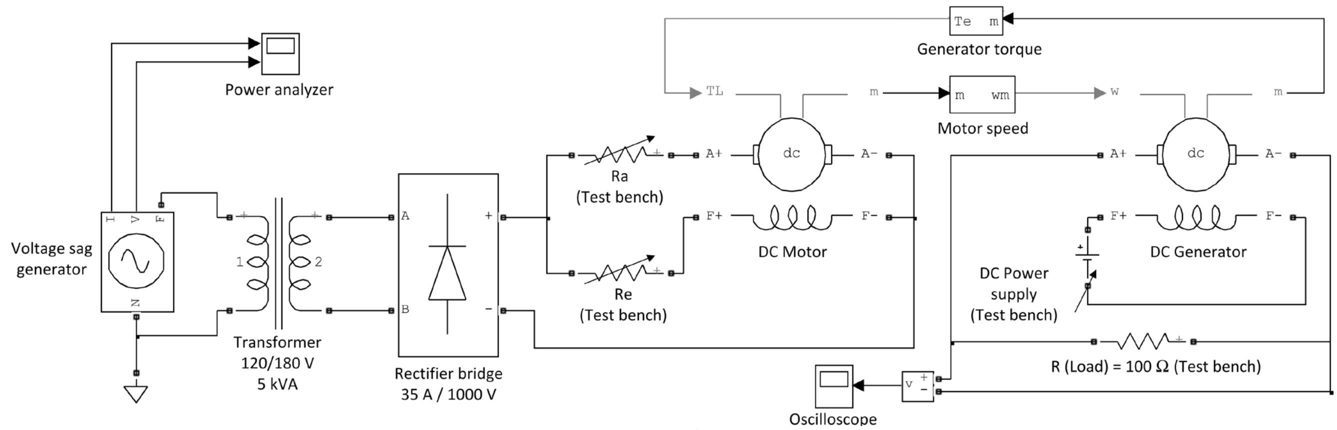

Fig. 7. Electrical scheme for the immunity test

TABLE III. EXPERIMENT RATED PARAMETERS

Voltage sag generator	
Output voltage (V)	114
Output current (A)	5.55
Primary DC power supply	
Output DC voltage (V)	182
DC motor DL 1024R	
Input DC voltage (V)	182
Motor speed (rpm)	3462
DC generator DL 1024R	
Output DC voltage (V)	130.2
Load (Ω)	100

Rated parameters of testing are presented in Table III. A primary DC power supply was built using a 5 kVA transformer (120/180 V) and a rectifier bridge (35 A, 1000 V). It was connected to the voltage sag generator for powering the DC motor. DC machines (motor and generator) were coupled by rotor axis. During testing, machines were powered with DC compound excitation, as shown in Figure 7. The DC motor-generator system was implemented for obtaining a DC voltage signal proportional to motor speed, which determines whether or not the EUT fails in a production process. The power quality analyzer was used to record voltage and current parameters supplied by the voltage sag generator to the EUT, whereas the oscilloscope showed the output voltage of the DC generator.

A. EUT response to a voltage sag

A 0.5 pu voltage sag with 100 ms of duration was caused for analyzing voltage and current supplied by the generator to the EUT. Measured results are shown in Figure 8 and Figure 9. It is observed that obtained waveforms are similar to those supplied by a commercial sag generator [17].

Voltage waveform in Figure 8 (a) shows the voltage sag, in which duration of 100 ms (about 6 cycles in 60 Hz) and amplitude of 81.5 V are verified. In Figure 8 (b), a decrease in current during sag is observed. Figure 9 (a) presents the voltage profile in the output of generator during testing, which shows the voltage sag of 59.4 Vrms and 100 ms. Current presents a decrease during sag, and a transient peak after the recovery point, as shown in Figure 9 (b).

Figure 10 shows the output signal of the DC generator (response of the EUT) observed in the oscilloscope during a 0.5 pu, 500 ms voltage sag. It can be seen from figure that DC voltage drops slowly with a constant slope from 130 VDC to 108 VDC during voltage sag, and then voltage recovers with a varying slope, as it is expected to be in motor speed.

(a)

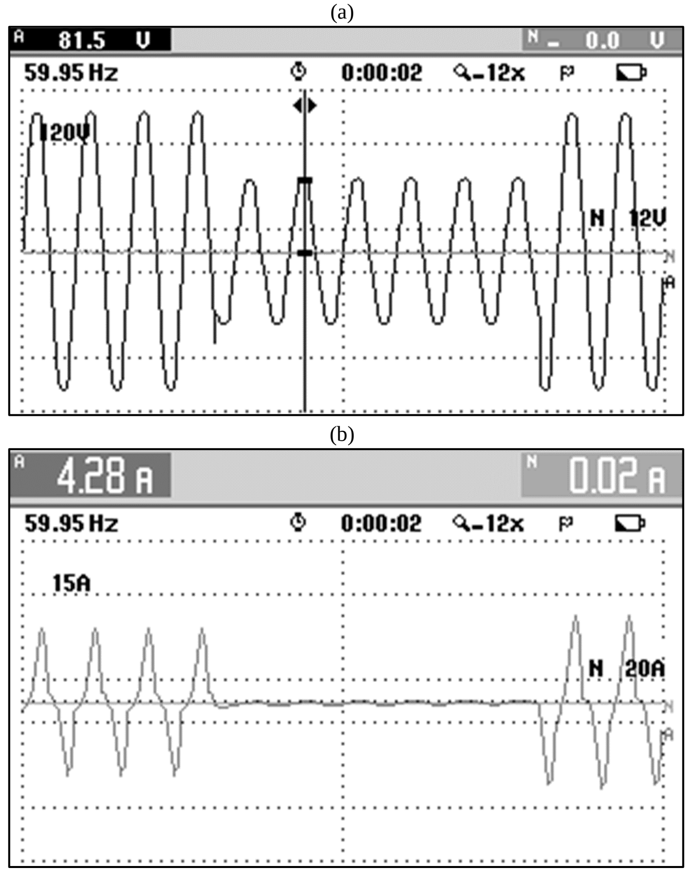

Fig. 8. (a) Voltage and (b) current waveforms supplied by the sag generator

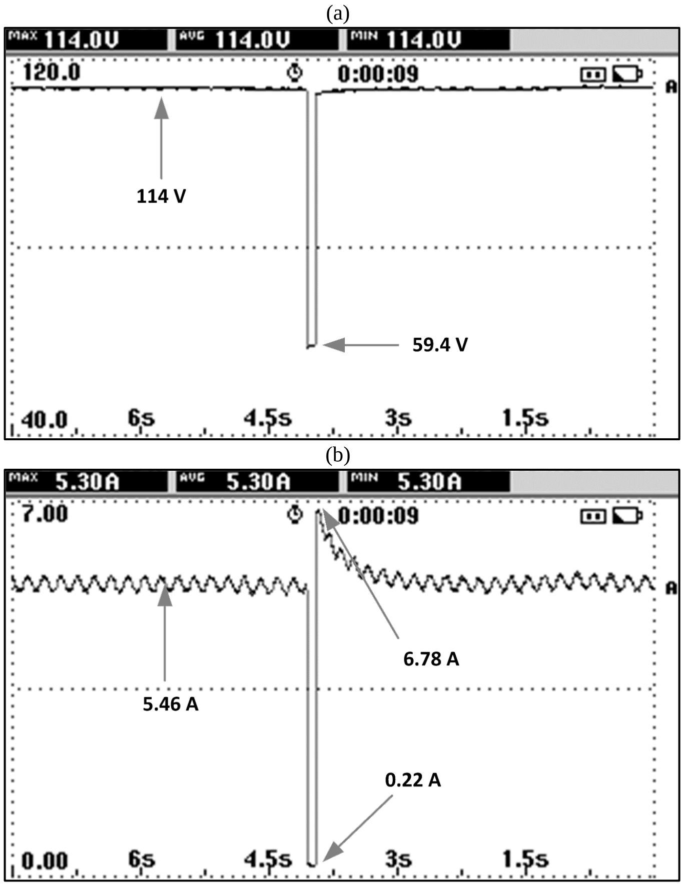

Fig. 9. (a) Voltage and (b) current profiles during sag

Fig. 10. Output voltage of the DC generator

B. *Immunity assessment for the EUT*

Immunity assessment operation mode of the voltage sag generator described in Section IV was used to achieve immunity assessment for the EUT, taking into account setting presented in Table IV. In the test, it was considered that the DC motor fails if the output voltage of the DC generator has a decrease greater than 10%. However, this reference may vary in other tests, depending on the production process characterization in which the motor is associated.

Tests were conducted with the voltage sag generator for determining duration for each magnitude in Table IV, in which the DC output voltage drops below 117 VDC (when drops below 10%). The oscilloscope was used to obtain the DC output signal.

The voltage tolerance curve is shown in Figure 11 and it was obtained with data presented in Table V. The area above the voltage tolerance curve represents magnitudes and durations of applied voltage in which the DC motor (EUT) operates normally. Voltage sags below the voltage tolerance curve result in malfunctioning of the DC motor.

TABLE IV. EXPERIMENT SET OF PARAMETERS

Duration		
Initial duration d (ms)	10	
Steps in duration t (ms)	50	
Magnitude		
Measure magnitude (V)	Switches	
	R_S	R_D
12.0	11	1
23.2	11	2
37.5	11	3
48.2	11	4
59.4	11	5
64.4	11	7
74.1	6	4
83.4	6	5
94.0	2	3
107.0	1	7

TABLE V. IMMUNITY TEST RESULTS

Measured magnitude (V)	Measured magnitud (pu)	Time of failure in the EUT (ms)
12.0	0.100	160
23.2	0.193	210
37.5	0.313	210
48.2	0.402	210
59.4	0.495	260
64.4	0.537	310
74.1	0.618	460
83.4	0.695	510
94.0	0.783	960
107.0	0.892	It does not fail

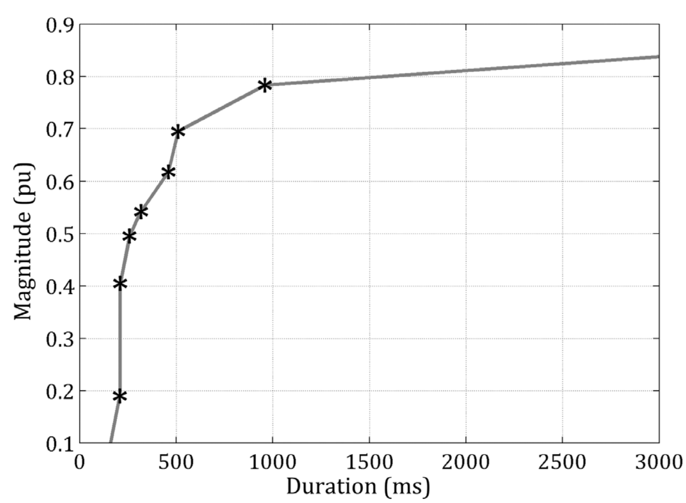

Fig. 11. Voltage tolerance curve of the DC motor

VI. CONCLUSION

The voltage tolerance curve is an appropriate tool for evaluating the performance of equipment during voltage sags, since they are affected mainly by magnitude and duration.

A prototype of single-phase voltage sag generator for testing electrical and electronic equipment has been designed and built, and given its compact, easy to be transported, and rated operating characteristics, it is concluded that it is feasible to implement a prototype for industrial applications in an academic context. During testing for validating the proposed immunity assessment methodology, similarity was observed between waveforms of voltage and current produced by the prototype, and waveforms in a commercial sag generator, whereas no distortion introduced and the current peaks were reproduced.

The built prototype is capable of controlling duration of voltage sags due to its high speed solid state switches, giving a high enough resolution (step size in time) to apply the developed methodology for assessing equipment immunity. Nevertheless, the prototype has a limited resolution in magnitude steps, because it depends on EUT impedance, hence, the methodology to assess immunity must be adaptable to different steps in magnitude.

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