SYMMETRICAL COMPONENTS BASED VOLTAGE SAG GENERATOR – CONCEPT AND SIMULATIONS

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***Abstract* – This paper proposes a new voltage sag generator for testing electric sensitive electronic equipment. This generator works with frequency inverters and its control is based on voltages symmetrical components that will be injected in series with original utility voltages and will create the voltage sag. The paper discusses about the concept, calculations and simulations involved in this kind of voltage sag generator.**

***Keywords* – Voltage sag generator, symmetrical component.**

I. INTRODUCTION

The utility concern about power quality began in the 80's. Before that, main discussions were about power generation and transmission.

One of the main reasons for this scenario is the development of electronic equipment. Besides a piece of these equipment pollutes energy buses with harmonics and other electric faults, others are too sensitive to voltage variations. So, many electronic equipment can suffer damage from voltage sags and, in other cases, they can be turned off by some protection device. These inconveniences mean loss of productivity to industries and consequently, loss of money.

Another reason that increased studies on power quality was the need to make a standard of supplied energy parameters, like voltage, harmonic distortion, etc. As a result, consumers were now seen as clients and not only a load in a power system. Energy became a product with some characteristics that need to be measured, guaranteed and improved.

This standardization only happened due to the development of electric measurement equipment, that were able to measure other parameters besides voltage and current, like harmonic distortion and voltage sags.

Power quality is a theme that discusses many other issues, such as the presence and measurement of harmonic distortion and measurement of the supplied voltage. This paper will focus on study and generation of voltage sags. The generator will work with frequency inverters with control based on symmetrical components (positive, negative and zero sequence). This new technique will make possible the generation of any type of voltage sag.

This voltage sag generator will be useful to test and validate VSI inverters and UPS systems. Nowadays, it's very important to know how these equipment works when a voltage sag occur. Many industries have frequency inverters and, sometimes, these inverters stop due to voltage sags. Consequently, the process where these inverters are involved stops too.

The paper focus on the concept and simulation of the symmetrical component voltage sag generator. In future studies, it's intended to implement this voltage sag generator in order to test some inverters and UPS systems.

On item II-A, the paper shows the types of voltage sags and how they vary their phase and magnitude depending on the sag percent deep. Item II-B explains the concept and calculations of the proposed voltage sag generator. Finally, item II-C exposes some simulations of the proposed voltage sag.

II. CONTENTS

A. Voltage Sag

Among different definitions about voltage sag, the paper defines voltage sags as voltage reductions (from 10 to 90% of nominal magnitude) in a short time interval (from half-cycle to few minutes) [1]. Voltage sags occur due to several reasons, like short-circuits, overflow, animal contact with transmissions lines and large motors starts.

Three-Phase voltage sag can be classified in seven types as shown at figure 1. Table I presents the relation involving voltage phase and magnitude and the remained voltage "V" due to sag in pu [1].

TABLE I
Phase and magnitude of each voltage sag type

Sag Type A $V_a = V$ $V_b = -\frac{1}{2}V - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}V + \frac{1}{2}jV\sqrt{3}$	Sag Type B $V_a = V$ $V_b = -\frac{1}{2} - \frac{1}{2}j\sqrt{3}$ $V_c = -\frac{1}{2} + \frac{1}{2}j\sqrt{3}$
Sag Type C $V_a = 1$ $V_b = -\frac{1}{2} - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2} + \frac{1}{2}jV\sqrt{3}$	Sag Type D $V_a = V$ $V_b = -\frac{1}{2}V - \frac{1}{2}j\sqrt{3}$ $V_c = -\frac{1}{2}V + \frac{1}{2}j\sqrt{3}$
Sag Type E $V_a = 1$ $V_b = -\frac{1}{2}V - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}V + \frac{1}{2}jV\sqrt{3}$	Sag Type F $V_a = V$ $V_b = -\frac{1}{3}j\sqrt{3} - \frac{1}{2}V - \frac{1}{6}jV\sqrt{3}$ $V_c = +\frac{1}{3}j\sqrt{3} - \frac{1}{2}V + \frac{1}{6}jV\sqrt{3}$
Sag Type G $V_a = \frac{2}{3} + \frac{1}{3}V$ $V_b = -\frac{1}{3} - \frac{1}{6}V - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{3} - \frac{1}{6}V + \frac{1}{2}jV\sqrt{3}$	

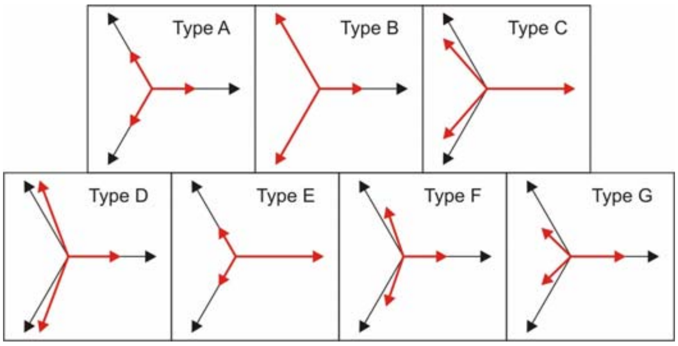

Fig. 1 – Voltage sag types

With the voltage sag type on figure 1 and its relation exposed on table I, it's possible to calculate which vectors will compose the voltage sag.

B. Symmetrical component based voltage sag generator

There are three usual types of voltage sag generators: variable transformers, load commutation (like reactors, motors, etc) and power amplifiers. The first one combines different transformers that will generate voltage sag or nominal voltage. Electronic switches modify which voltage will be on the load. The second one uses variables loads to cause voltage sag that can practically happen in an industry [7]. The last one generates waveforms that will be injected on an electric bus to compose voltage sag. This type makes possible modify any parameter of voltage sag [5,6]. Therefore, the proposed voltage sag generator is based on the last type of sag generators.

The generator control technique is based on symmetrical components. An algorithm was developed to make calculations easier and help simulations projects. Type of voltage sag and its magnitude are algorithm inputs, while symmetrical components voltages are outputs. The steps of the algorithm are:

1) Voltage sag type: among the 7 types, generated voltage sag type is chosen in this step.

2) Voltage sag magnitude: as defined before, the magnitude of the voltage sag is chosen. This value can be 10% to 90% of the nominal value (according to IEEE).

3) Voltage sag vectors: in this step, voltage sag vectors are calculated according to table I.

4) Injected voltage vectors: the injected voltage vectors V_{as}, V_{bs}, V_{cs} are defined as (1).

$$\begin{aligned} V_{as} &= V_a - V_a' \\ V_{bs} &= V_b - V_b' \\ V_{cs} &= V_c - V_c' \end{aligned} \qquad (1)$$

Where V_a, V_b e V_c are remained voltage sag vectors and V_a', V_b' e V_c' are nominal voltage vectors.

5) Symmetrical component calculation of injected voltage vectors: the last step of the algorithm is the calculation of symmetrical components of each voltage vector that will be injected.

Table II shows voltage vectors that will be injected for any magnitude "V" of each voltage sag type. Table III shows symmetrical components voltages V_{as1}, V_{as2}, V_{as0} (positive, negative and zero sequence, respectively) for any magnitude "V" for each voltage sag type. Theses calculations were made for phase A of each symmetrical component sequence, because the other vectors (B and C) are phased 120º from A, depending on each sequence.

TABLE II
Injected voltage vectors

Sag Type A $V_{as} = (1-V)e^{-180j}$ $V_{bs} = (1-V)e^{60j}$ $V_{cs} = (1-V)e^{-60j}$	Sag Type B $V_{as} = (1-V)e^{-180j}$ $V_{bs} = 0$ $V_{cs} = 0$
Sag Type C $V_{as} = 0$ $V_{bs} = \frac{\sqrt{3}}{2}(1-V)e^{90j}$ $V_{cs} = \frac{\sqrt{3}}{2}(1-V)e^{-90j}$	Sag Type D $V_{as} = (1-V)e^{-180j}$ $V_{bs} = \frac{1}{2}(1-V)e^{0j}$ $V_{cs} = \frac{1}{2}(1-V)e^{0j}$
Sag Type E $V_{as} = 0$ $V_{bs} = (1-V)e^{60j}$ $V_{cs} = (1-V)e^{-60j}$	Sag Type F $V_{as} = (1-V)e^{-180j}$ $V_{bs} = 0{,}5774(1-V)e^{30j}$ $V_{cs} = 0{,}5774(1-V)e^{-30j}$
Sag Type G $V_{as} = \frac{1}{3}(1-V)e^{-180j}$ $V_{bs} = 0{,}8819(1-V)e^{79{,}1j}$ $V_{cs} = 0{,}8819(1-V)e^{-79{,}1j}$	

TABLE III
Symmetrical components voltage vectors

Sag Type A $V_{as1} = (1-V)e^{-180j}$ $V_{as2} = 0$ $V_{as0} = 0$	Sag Type B $V_{as1} = \frac{1}{3}(1-V)e^{-180j}$ $V_{as2} = \frac{1}{3}(1-V)e^{-180j}$ $V_{as0} = \frac{1}{3}(1-V)e^{-180j}$
Sag Type C $V_{as1} = \frac{1}{2}(1-V)e^{-180j}$ $V_{as2} = \frac{1}{2}(1-V)e^{0j}$ $V_{as0} = 0$	Sag Type D $V_{as1} = \frac{1}{2}(1-V)e^{-180j}$ $V_{as2} = \frac{1}{2}(1-V)e^{-180j}$ $V_{as0} = 0$
Sag Type E $V_{as1} = \frac{2}{3}(1-V)e^{-180j}$ $V_{as2} = \frac{1}{3}(1-V)e^{0j}$ $V_{as0} = \frac{1}{3}(1-V)e^{0j}$	Sag Type F $V_{as1} = \frac{2}{3}(1-V)e^{-180j}$ $V_{as2} = \frac{1}{3}(1-V)e^{-180j}$ $V_{as0} = 0$
Sag Type G $V_{as1} = \frac{2}{3}(1-V)e^{-180j}$ $V_{as2} = \frac{1}{3}(1-V)e^{0j}$ $V_{as0} = 0$	

A software was developed with this algorithm on Matlab®. In this software, the user chooses which type of voltage sag and how deep is it. From this, the software calculates all vectors above and outputs voltage vectors that will be injected in symmetrical components form.

Voltage sag generator topology is shown at figure 2 and it has basically PWM frequency inverters, chopper dc supplies and transformers. PWM Inverters represent each symmetrical component sequence (positive, negative and zero), while transformers are responsible by adding voltages that will be generated by inverters. Three-phase inverter 1 will generate positive sequence, while three-phase inverter 2 and one-phase inverter will generate negative and zero sequence, respectively.

Symmetrical components topology brings flexibility in characterization of voltage sag. It's possible to modify magnitude and phase of voltage sag modifying vectors that will be added on each sequence.

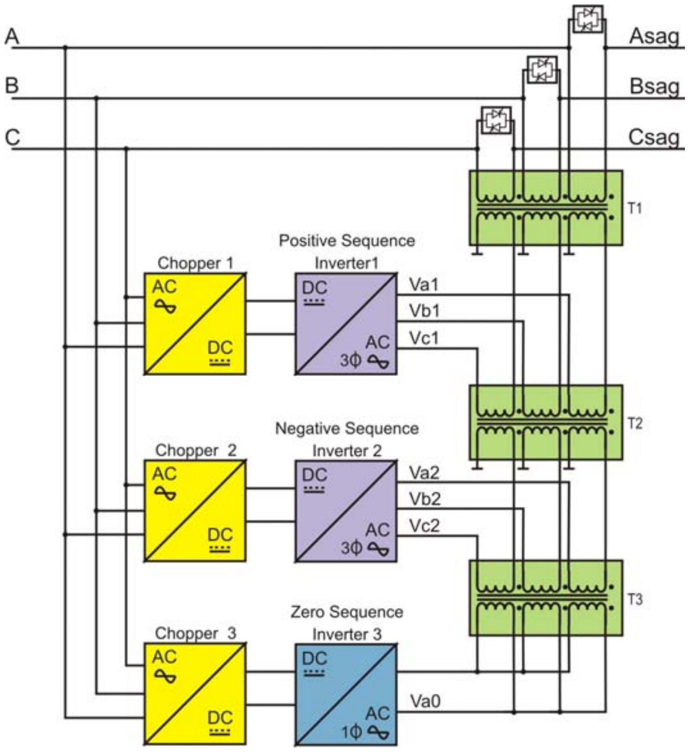

Fig. 2 – Proposed voltage sag generator

The 1-phase inverter on figure 3 is a full-bridge inverter or H-bridge inverter with PWM modulation and a LC filter in its output [3,4]. This inverter has four interrupters and is responsible to generate zero sequence vectors.

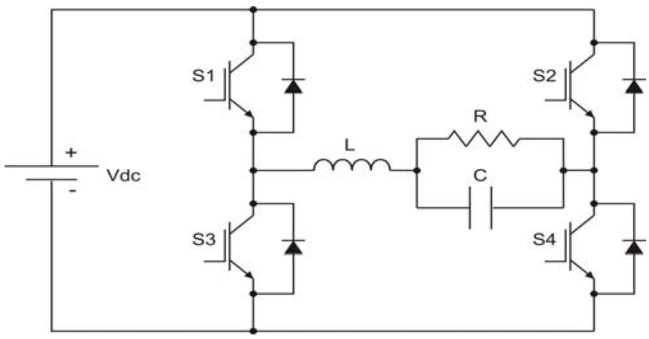

Fig. 3 – 1-phase inverter topology

Three-phase inverters on figure 4 have six interrupters and are controlled with PWM technique [3]. Also, as in the 1-phase inverter, these inverters have LC filter in their outputs to turn output voltage most sinusoidal as possible.

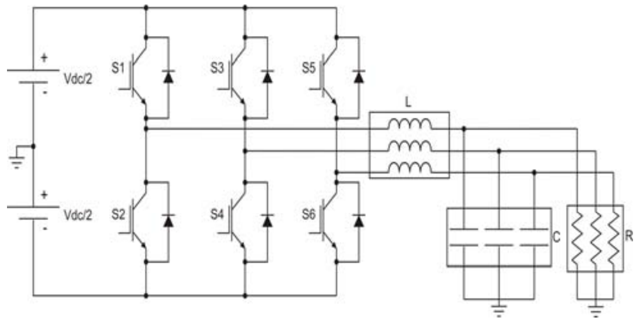

Fig. 4 – 3-phase inverter topology

Varying correctly the duty cycle of PWM gates and projecting adequately LC filters parameters [4], a sinusoidal voltage with magnitude and phase specified with low harmonic distortion can be generated.

The voltage sag control will be an open loop control that needs to compensate magnitude and phase variations due to filters and transformers. Magnitude attenuations can be corrected by multiplying the desirable voltage output by a constant gain and phase variations can be corrected by adding or subtracting a constant phase angle.

C. Voltage sag generator simulation

As a way to validate the theory of the proposed voltage sag generator, some simulations results are presented. These simulations were done in Simulink and SimPower Systems of Matlab® and followed the parameters on table IV.

TABLE IV
Simulation parameters

Voltage sag type	A
Magnitude V	0,5 ou 50%
Initial time of voltage sag	4 periods of signal (66,66ms)
End time of voltage sag	After 10 periods of signal (166,66ms)
Vdc	622Vdc
Inverter frequency	4kHz
Output Power Pout	50kVA
Vout (RMS)	440V
THD	Less than 5%
Inductance L of filters	1000uH
Capacitance C of filters	200uF

The voltage sag simulated was type A because this is one of the most dangerous voltage sag that trips VSI inverters. According to the software developed and some parameters on Table IV, symmetrical components voltages vectors will be as shown in (2).

$$\begin{aligned} V_{as1} &= 0{,}5e^{-180j} \\ V_{as2} &= 0 \\ V_{as0} &= 0 \end{aligned} \qquad (2)$$

As it can be seen, these vectors are an equilibrated vector system. Therefore, only positive sequence is available. Then, inverters 2 and 3 will not operate and the injected vector will be added just by inverter 1. These vectors will have exactly 0.5 of nominal magnitude. Figure 5(a) shows simulation injected voltages waveforms and figure 5(b) shows these voltages in RMS values.

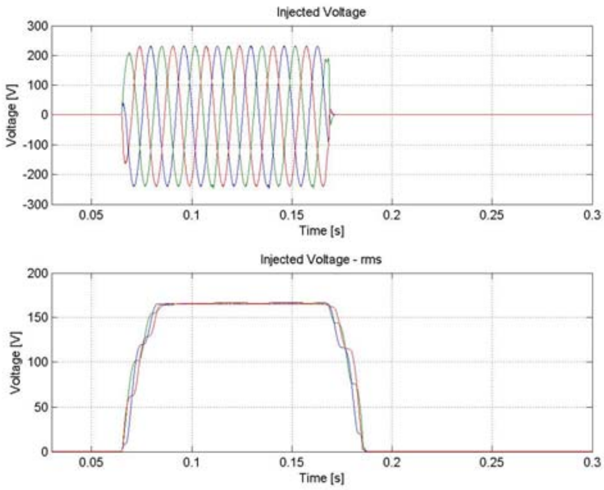

Fig. 5 – Injected voltages sag A 50%

On figure 6(a), output voltage waveforms are illustrated. It can be seen that there is a voltage sag between 66,66 [ms] and 166,66 [ms], exactly the specified voltage sag duration time – 100 [ms]. Also it can be seen that the voltage output is 50% smaller than nominal voltage. Figure 6(b) shows output RMS voltages, where can be seen that the voltage sag has a rectangular shape.

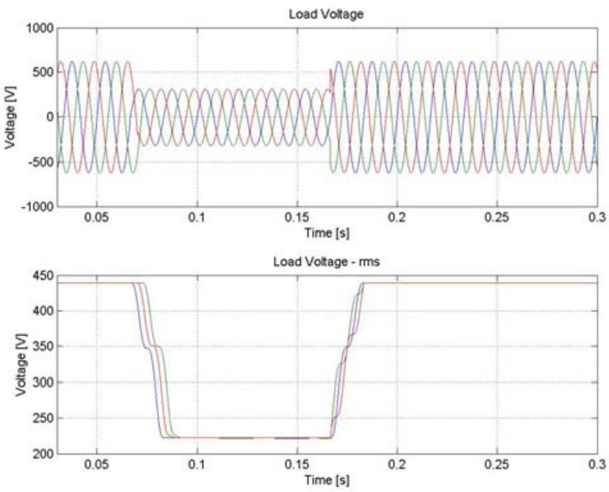

Fig. 6 – Output voltages with sag A 50%

Besides these simulations, it is interesting vary voltage sag deep. So, new parameters simulations were established according to Table V.

TABLE V
Simulation parameters

Voltage sag type	A
Magnitude V	0,65 ou 65%
Initial time of voltage sag	4 periods of signal (66,66ms)
End time of voltage sag	After 10 periods of signal (166,66ms)

In this case, the injected voltages will be according to (3).

$$\begin{aligned} V_{as1} &= 0{,}35e^{-180j} \\ V_{as2} &= 0 \\ V_{as0} &= 0 \end{aligned} \qquad (3)$$

Figures 7(a) and 7(b) show injected voltages waveforms and RMS values.

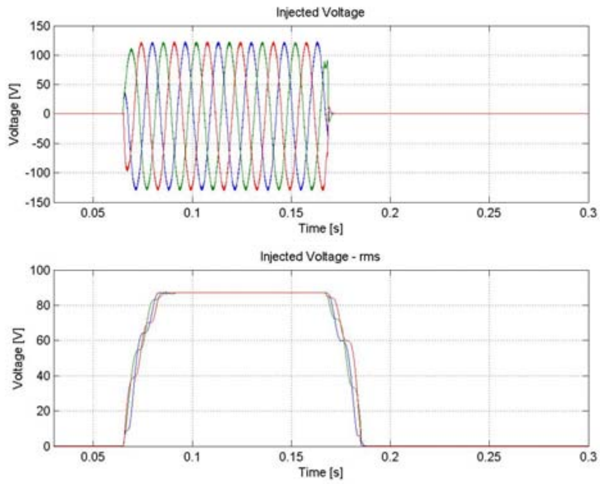

Fig. 7 – Injected voltages sag A 65%

Figure 8(a) and 8(b) show output voltage waveforms and RMS values. The voltage sag duration time is the same as the other simulations – 100 [ms].

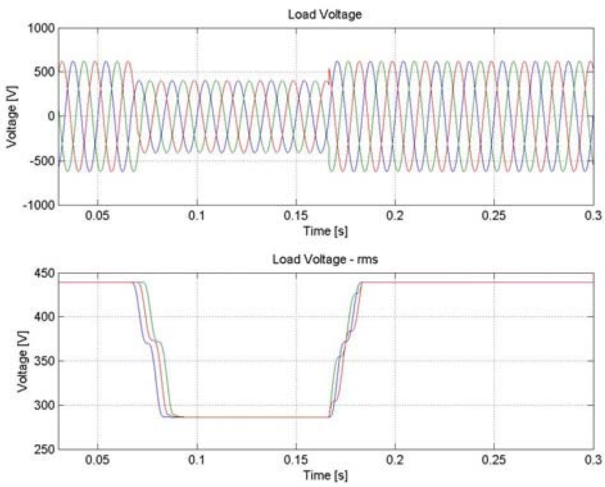

Fig. 8 – Output voltages with sag A 65%

In all these simulations, voltage sag has a rectangular shape and how it's a type A sag, voltage output phase didn't vary with voltage sag deep.

III. CONCLUSION

The concept of voltage sag generator based on symmetrical component is efficient and applicable to any voltage sag type and magnitude. Based on the developed software and the simulations results, the generator concept is valid and results in interesting results.

Choosing right topologies and filters, it's possible to generate sinusoidal voltages with low harmonic distortion and magnitudes that can vary according to voltage sag magnitude.

Simulations results presented in this paper showed voltage sags due to three-phase fault (type A sag), one of the most dangerous voltage sag that trip VSI inverters.

Next studies will be related to practical applicability and implementation of the proposed voltage sag generator on testing electronic equipment, such as VSI frequency inverters and UPS systems.

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