Symmetrical and Unsymmetrical Voltage Sag Effects on the Three-phase Synchronous Machine Stability

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Keywords

«Synchronous motor», «Modelling», «Simulation», «Power Quality»

Abstract

This paper focuses on the effects of voltage sags, both symmetrical and unsymmetrical, on the three-phase Synchronous Machine (SM). Voltage sags on SM cause speed variations, current and torque peaks and hence may cause tripping and equipment damage. The consequences of voltage sags on the machine behaviour depend on different factors such as sag's magnitude (or depth), duration, initial point-on-wave and the parameters of the electrical machine. In this study, three SMs of different rated power have been considered in order to simulate the voltage sag effects for specific conditions and analyze the machine stability.

I. Introduction

The vast majority of the electrical power generation systems consist of synchronous generators coupled to the electrical grid through a transformer. This is due to its capability of generating electricity in large scale power plants [1]. Large synchronous generators are also used on cogeneration applications. Small synchronous generators (in the kVA range) can be used not only for emergency power sources for hospitals, military facilities and industry in case a blackout takes place, but also in isolated systems, where the generator is driven with a small combustion engine as a prime-mover.

During the last years, the power quality has gained a great importance in the industry because more equipment is sensitive to supply perturbations. The electrical grid may present many types of disturbances, being the voltage sag the most common. A voltage sag is a short-duration (from half cycle to 1 minute) drop between 10% and 90% in the magnitude of the *rms* voltage. The most common cause of voltage sags are faults, large transformer energizing and large motor starting [2-3].

The interest in studying this kind of disturbances is mainly due to the problems that they cause in electrical equipments. Voltage sags on SM may cause large torque peaks that can damage the shaft or the equipment connected to the shaft. In addition, voltage sags may cause tripping that leads to financial losses. The simulation of the SM's behaviour under voltage sags permits defining different criteria for protecting and preventing potential damages in such machines.

The aim of this work is to analyse the SM behaviour against voltage sags. Section II presents the SM model. Section III shows the voltage sags classification. Finally, based on the simulations, voltage sag effects on SM are analyzed in Section IV.

II. Synchronous machine model

In this paper the SM generic model is used considering its dynamic equations in the *dq* reference frame given by [4]. Damper windings exist in both *d* and *q* axis:

$$\frac{d}{dt}\left(\mathbf{i}_p\right) = \mathbf{M}_p^{-1}\left\{\mathbf{v}_p - \mathbf{R}\mathbf{i}_p - \boldsymbol{\omega}\mathbf{M}_p\mathbf{i}_p\right\} \quad (1)$$

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left\{\Gamma(t) - \Gamma_{load}(t)\right\} \quad (2)$$

$$\frac{d\theta}{dt} = \omega_m \quad (3)$$

where $\mathbf{i}_p$ is the vector which contains the Park's stator and rotor currents, $\mathbf{v}_p$ is the vector that includes the transformed stator and rotor voltages, $\mathbf{R}$ is the winding resistance matrix and $\mathbf{M}_p$ is the transformed inductance matrix. The instantaneous electromagnetic torque $\Gamma(t)$ and the load angle $\delta(t)$ (measured in steady-state from phasor $\underline{E}_s$ to phasor $\underline{U}_s$) are expressed as:

$$\Gamma(t) = i_{sq}\left(M_{dF}i_F + M_{dD}i_D\right) - i_{sd}\left(M_q i_Q\right) + \left(L_d - L_q\right)i_{sd}i_{sq} \quad (4)$$

$$\delta(t) = \left(\omega_s t + \varphi_s\right) - \left(\theta(t) + \pi/2\right) \quad (5)$$

Three SMs have been simulated: a high-speed steam turbine generator (835MVA), a low-speed hydro turbine generator (325MVA), both obtained from [4], and a small generator. The main rated data of these generators is shown in Table I.

Table I: Rated data of the simulated Synchronous Generator

RATED DATA OF 835MVA SYNCHRONOUS GENERATOR

$S_N = 835MVA$	$U_N = 26kV$	$\cos\varphi_N = 0.85$
$f_N = 60Hz$	$H = 5.6s$	$J = 65.8\ x10^3\ kg\ m^2$
$\omega_N = 3600\ rpm$	*1 pole pair*	

RATED DATA OF 325MVA SYNCHRONOUS GENERATOR

$S_N = 325MVA$	$U_N = 20kV$	$\cos\varphi_N = 0.85$
$f_N = 60Hz$	$H = 7.5s$	$J = 35.1\ x10^6\ kg\ m^2$
$\omega_N = 112.5\ rpm$	*32 pole pairs*	

RATED DATA OF 5KVA SYNCHRONOUS GENERATOR

$S_N = 5kVA$	$U_N = 437V$	$\cos\varphi_N = 0.85(i)$
$f_N = 60Hz$	$H = 3.55s$	$J = 0.2498\ kg\ m^2$
$\omega_N = 3600\ rpm$	*1 pole pair*	

III. Sags classification and characterization

Voltage sags can be either symmetrical or unsymmetrical, depending on the causes. If the individual phase voltages are equal in magnitude and the phase displacement is 120^o, the sag is symmetrical. Otherwise, the sag is unsymmetrical.

According to [2] voltage sags can be grouped into seven types, denoted as A, B, C, D, E, F and G. Table II shows their expressions (where *h* is the sag depth) and Fig. 1 shows their phasor diagrams.

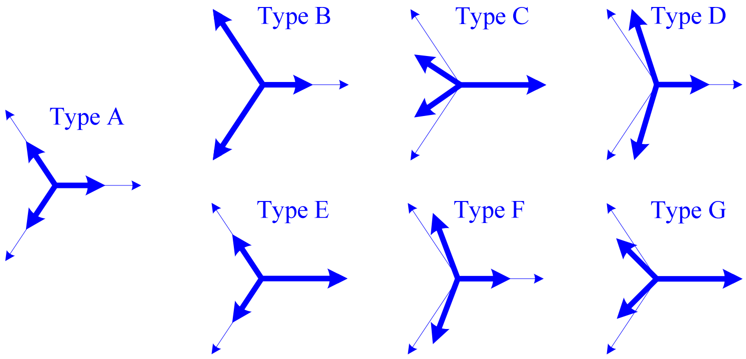


Fig. 1: Voltage sag types: Symmetrical (type A) and unsymmetrical (types B - G). All sags have a depth of 50%. (Obtained from [2]).

In order to simulate the behaviour of a SM, it has been considered that the sag shape is rectangular, no phase jump occurs and the sag type does not change when the fault is cleared. Hence, the voltage sags are defined by their depth h ($0.1 \le h \le 0.9$), their duration Δt, and their initial point-on-wave ψ_i, as well as their type.

Table II: Sag Types in Equation Form (Obtained from [2])

Type A	Type B	Type C	Type D
$\underline{V}_a = hV$ $\underline{V}_b = -\frac{1}{2}hV - j\frac{\sqrt{3}}{2}hV$ $\underline{V}_b = -\frac{1}{2}hV + j\frac{\sqrt{3}}{2}hV$	$\underline{V}_a = hV$ $\underline{V}_b = -\frac{1}{2}V - j\frac{\sqrt{3}}{2}V$ $\underline{V}_b = -\frac{1}{2}V + j\frac{\sqrt{3}}{2}V$	$\underline{V}_a = hV$ $\underline{V}_b = -\frac{1}{2}V - j\frac{\sqrt{3}}{2}hV$ $\underline{V}_b = -\frac{1}{2}V + j\frac{\sqrt{3}}{2}hV$	$\underline{V}_a = hV$ $\underline{V}_b = -\frac{1}{2}hV - j\frac{\sqrt{3}}{2}V$ $\underline{V}_b = -\frac{1}{2}hV + j\frac{\sqrt{3}}{2}V$
Type E	**Type F**	**Type G**	
$\underline{V}_a = V$ $\underline{V}_b = -\frac{1}{2}hV - j\frac{\sqrt{3}}{2}hV$ $\underline{V}_b = -\frac{1}{2}hV + j\frac{\sqrt{3}}{2}hV$	$\underline{V}_a = hV$ $\underline{V}_b = -\frac{1}{2}hV - j\frac{1}{\sqrt{12}}(2+h)V$ $\underline{V}_b = -\frac{1}{2}hV + j\frac{1}{\sqrt{12}}(2+h)V$	$\underline{V}_a = \frac{1}{3}(2+h)V$ $\underline{V}_b = -\frac{1}{6}(2+h)V - j\frac{\sqrt{3}}{2}hV$ $\underline{V}_b = -\frac{1}{6}(2+h)V + j\frac{\sqrt{3}}{2}hV$	Where: $h = 0.1 \ldots 0.9$ sag depth $V = U_L/\sqrt{3}$ phase-to-ground AC voltage

IV. Voltage sag effects

The most relevant voltage sag effects on the SM behaviour are speed variations, with possible loss of synchronism, current and torque peaks, as well as tripping protection. The machine behaviour is different when symmetrical and unsymmetrical sags are produced in the grid.

When symmetrical sag is applied to the SM, the most severe peaks occur at the beginning and at the end of the sag, because symmetrical sags have not negative sequence voltage, thus the waveform is not oscillatory. Fig. 2(a) shows the transient effects caused by a symmetrical sag on the 5kVA SM.

Fig. 2(b) shows the SM behaviour against an unsymmetrical voltage sag type E on the 5kVA SM. In this case, the instantaneous active and reactive power has a higher distortion, but their peak values are smaller when the sag starts as well as when the sag ends. It is due to the fact that the positive sequence voltage applied to the machine is higher for the unsymmetrical sag than for the symmetrical sag [5].

Since the machine losses are small and the machine speed is nearly constant, the torque and the active power have the same waveform. The reactive power (showed in dotted line in Fig. 2) has an oscillatory behaviour for all the unsymmetrical sags because of their negative sequence voltage.

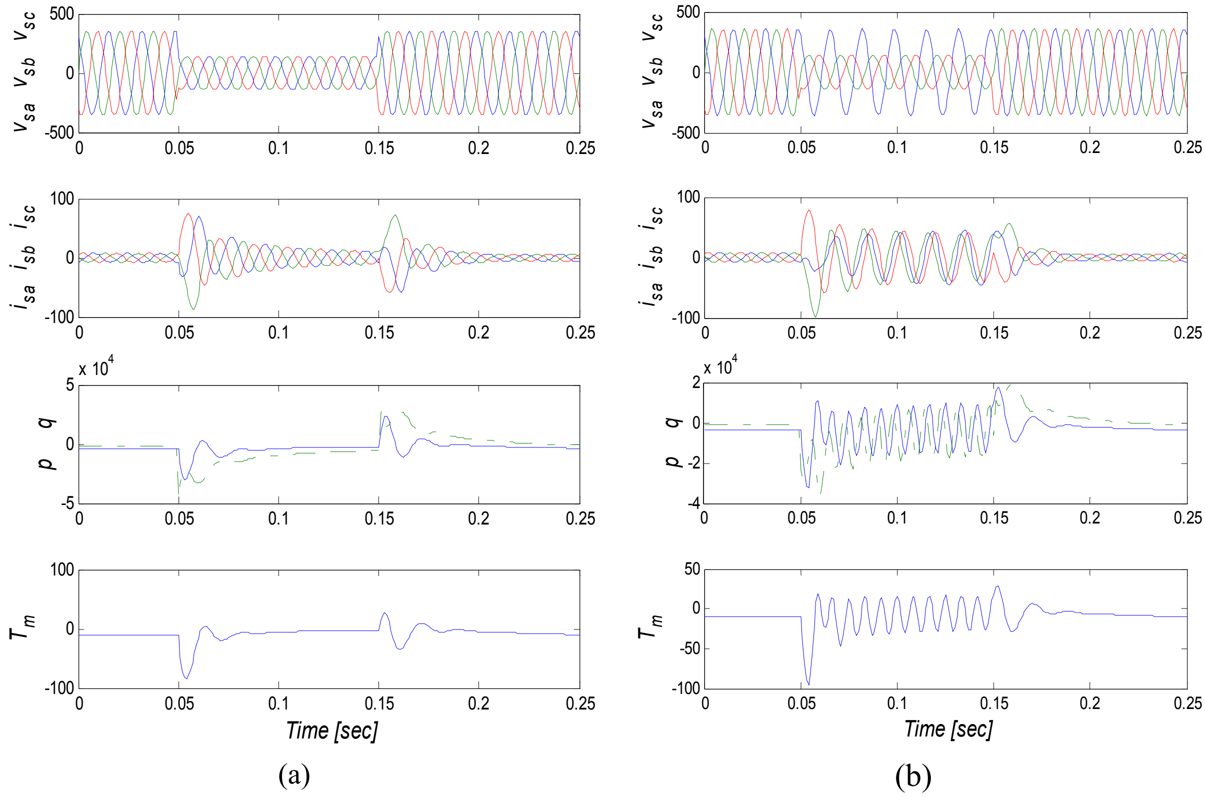


Fig. 2: 5kVA Synchronous Machine behaviour due to a voltage sag: (a) symmetrical type A, $h = 0.4$, $\Delta t = 100$ms, $\psi_i = 15^o$, (b) unsymmetrical type E, $h = 0.4$, $\Delta t = 100$ms, $\psi_i = 15^o$

On the whole, the waveform of the current and torque caused by voltage sag depends on different factors such as its depth, initial point-on-wave and duration, as well as the machine parameters. A brief description of these factors is given below.

A. Depth influence

The machine behaviour is inversely affected by the sag depth. As has been commented previously, a sudden drop in the voltage supply produces a current peak at the beginning of the sag and another current peak when the fault is cleared and the voltage is restored. After reaching the first peak value, an oscillation is produced with constant frequency (the grid's one) and decreasing amplitude. These current peaks are more severe if the sag is deeper. The same behaviour is observed for the torque for all depths.

B. Initial point-on-wave influence on the initial torque peaks

Initial point-on-wave is an important issue in the study of the sag effects. Consequently, different initial point-on-wave can produce peaks with different amplitude. Fig. 3 shows the initial torque peaks versus the initial point-on-wave (on the hydro turbine synchronous generator) for sag types A, B, C, D, E, F and G. For all simulations, depth sag is 10% and duration sag is 50ms. The initial torque peaks for the steam turbine synchronous generator have a similar behaviour.

As can be deduced from Fig. 3, the worst initial peaks occur near the initial point-on-wave of 90 degrees for the sag types B, D and F, while as far as the sags type C, E and G are concerned, the worst ones are around zero degrees. In addition, figures show that if the sag is symmetrical (type A), the initial point-on-wave has no influence on the initial torque peaks.

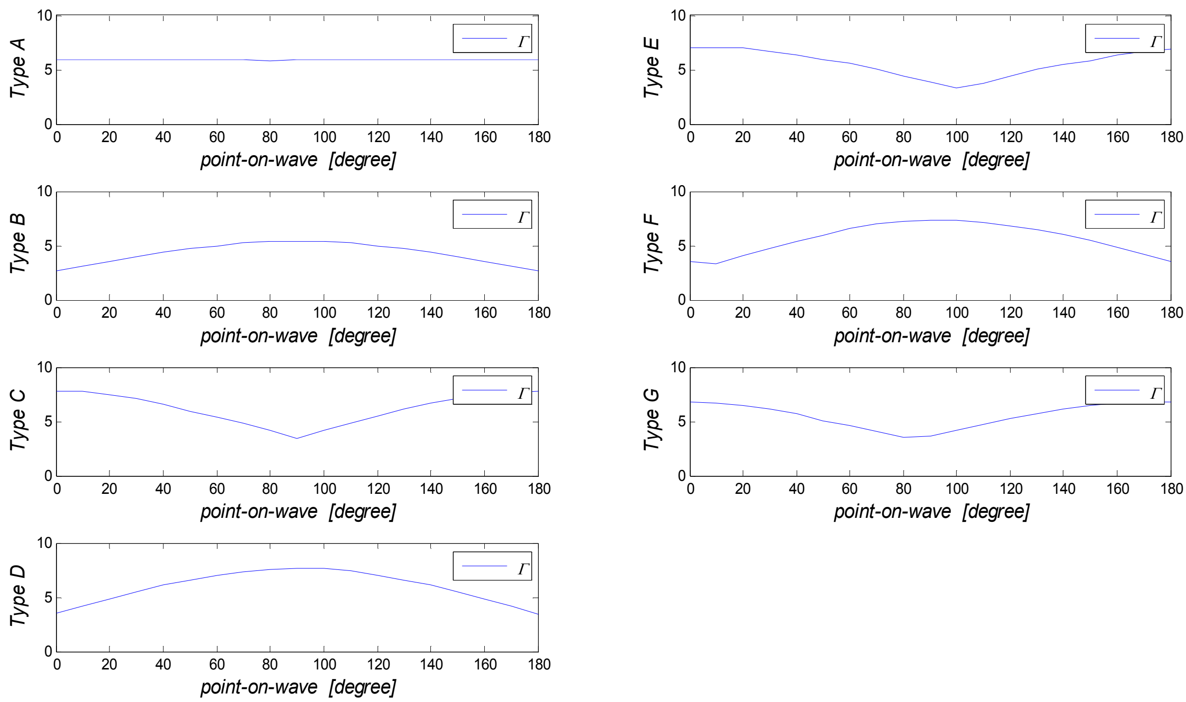
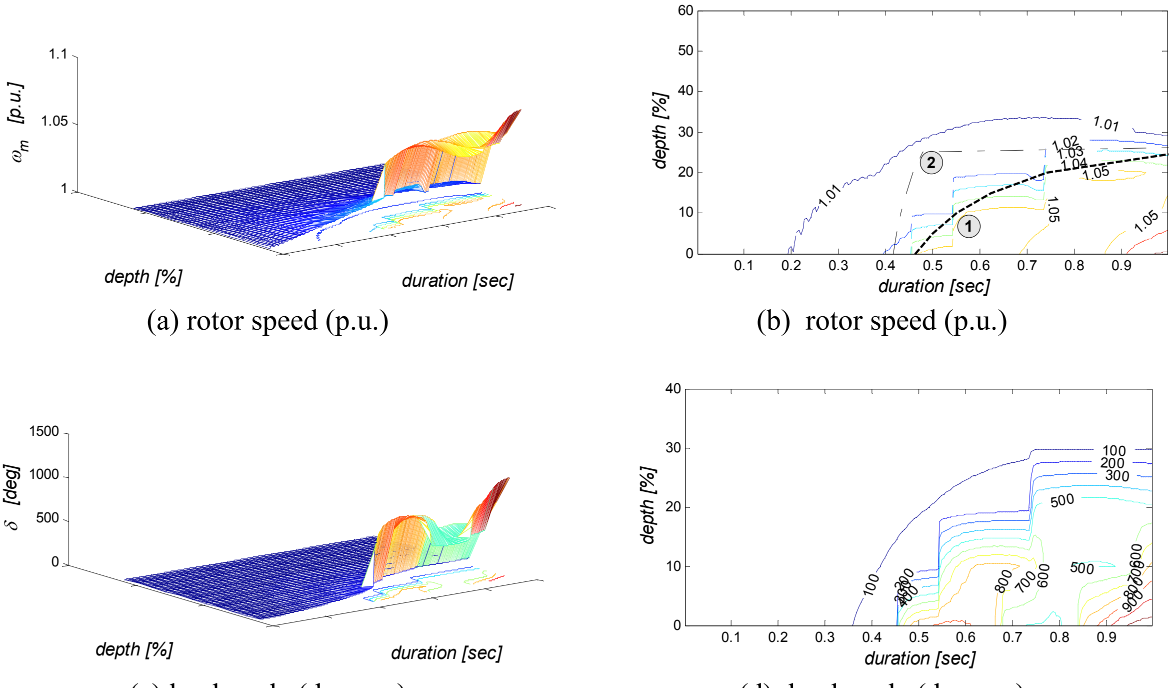


Fig. 3. Initial point-on-wave influence on the initial torque peaks (325MVA synchronous generator; values in per unit). Sag types A, B, C, D, E, F and G with different initial point-on-wave. (All sag types present the following parameters: $h = 0.1$, $\Delta t = 50$ms, $\psi_i = 0$ º to 180º)

C. Duration influence on the current peaks and the speed

Torque peaks due to sags with different durations have a periodical behaviour for all sag types. An increase in the sag duration leads to an increase in the current peaks when the sag ends. The same behaviour is observed for the three machines.



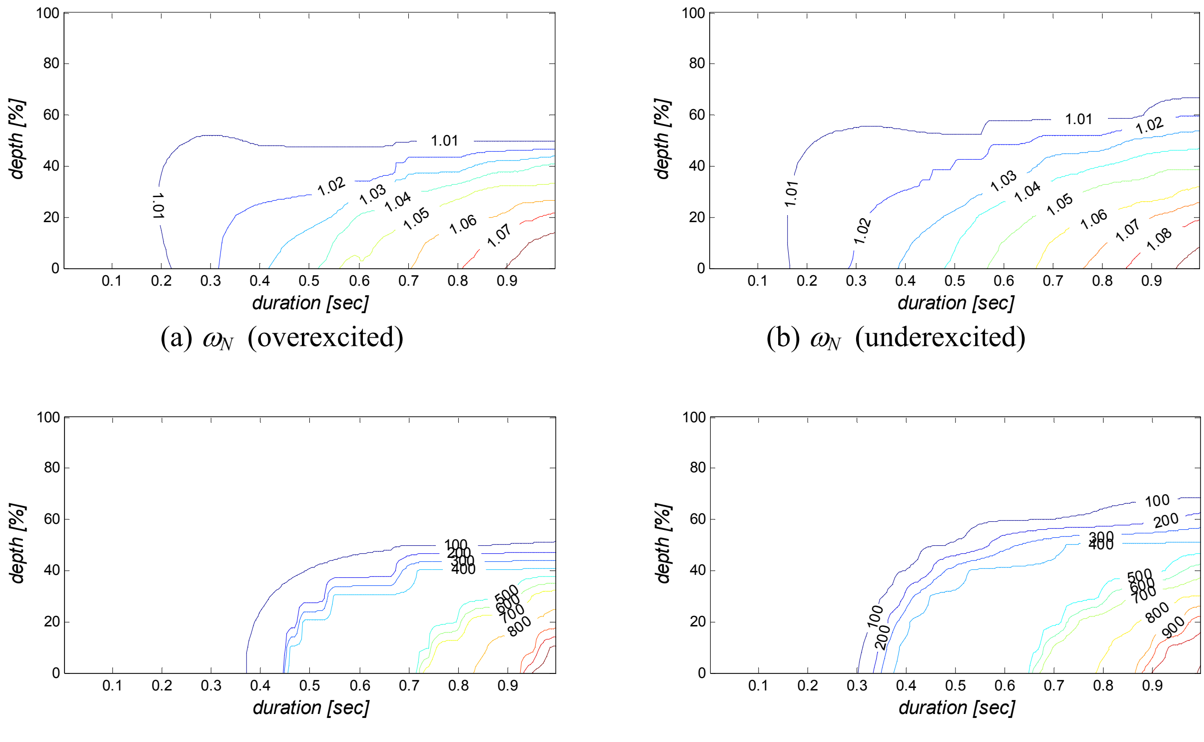
(a) rotor speed (p.u.)

(b) rotor speed (p.u.)

(c) load angle (degrees)

(d) load angle (degrees)

Fig. 4. Symmetrical voltage sag's duration and depth influence on the rotor speed (ω_N) and load angle (δ) of a 325MVA SM. (Sag type A, h = 0% to 100%, Δt = 0 to 1 second, ψ_i = 15 º)



(a) ω_N (overexcited)

(b) ω_N (underexcited)

(c) load angle (overexcited)

(d) load angle (underexcited)

Fig. 5. Symmetrical voltage sag's duration and depth influence on the rotor speed (ω_N) and load angle (δ) of a 5kVA synchronous generator. (Sag type A, h = 0% - 100%, Δt = 0 - 1second, ψ_i = 15 º).

As far as rotor speed is concerned, SM may lose synchronism for the most severe voltage sags (large duration and depth). This can be observed in Fig. 4, where several symmetrical sags applied to a hydro turbine synchronous generator have been simulated. Both figures (Fig. 4(a) and (b)) are the result of recursive simulations with depth h = 0% to 100% and duration Δt = 0 to 1 second. In this case, the initial point-on-wave is kept at 15º for all simulations. The thick dotted line (identified with number one) in Fig. 4(b) indicates the stability machine limits (when the synchronous generator is unable to return to its steady state value), obtained by using the dynamic equations of the SM. The thin dotted line (identified with number two) in the same figure, indicates the approximated limits of the machine's stability, obtained by using the equal-area criterion. The rotor speed peaks in the 835MVA steam turbine synchronous generator have a similar behaviour, but the synchronism is lost for shorter sag duration.

Another method for determining the loss of synchronism in the machine is the load angle. The ability to keep synchronism may be defined as the case when the load angle is below 180 º for all the time during and after the voltage sag [6]. This can be seen clearly in the Fig. 4(c) and 4(d).

Finally, the SM behaviour when it is overexcited is different from the behaviour when it is underexcited (considering either motor or generator mode of operation). An overexcited SM is more stable than an underexcited one [7]. This situation can be confirmed from Fig. 5, where several symmetrical sags have been simulated by considering a 5kVA SM working as a generator. In all the simulations the following parameters have been considered: depth h = 0% to 100%, duration Δt = 0 to 1 second and the initial point-on-wave is set in 15º. As it has been seen in Fig. 4 (b) and (c), the rotor speed of the overexcited generator is more stable (with deeper voltage sag and when the sag duration is larger) than the same generator when it is underexcited. Fig. 4(c) and 4(d) leads to the same conclusion.

V. Conclusion

Symmetrical and unsymmetrical voltage sag effects have been qualitatively analyzed on three different three-phase SMs. The simulations carried out allow us to understand the performance of SM and deduce its behaviour against disturbances in the power supply.

Voltage sag effects on equipment depend on different elements such as sag characteristics (depth, duration, point-on-wave and type of sag), equipment and grid. The depth and duration influence on the torque peaks are linear and periodical, respectively, for all sag types. The most relevant voltage sag effects on SM are current and torque peaks and possible loss of synchronism. It must be noted that there has been no significant differences in the simulation of the SM in a motor or generator mode of operation.

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