Role of Flywheel Energy Storage System in Microgrid

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Abstract—Recently, the idea of electricity generation from one side has changed by introducing the concept of microgrid. The latter enables not only producer to be consumer or vice versa. But to aggregate different renewable energy sources like solar and wind in order to mitigate CO_2 emission and produce clean energy, avoid big power losses, which are principally due both to the large electrical power produced in one place and long transmission lines .Nevertheless, this operation depends strongly on storage systems with power electronic converters for being reliable and controllable. In this context, a power electronic converter supplying a squirrel-cage induction machine coupled to a flywheel is proposed for study in this paper, This system is known as Flywheel Energy Storage System (FESS) and aims to improve the quality of electric power of grid or consumer by storing an amount of energy under kinetic form during high production of wind for example and to generate that quantity in case of deficit of primary source. The simulation results have been achieved using the software Matlab/Simulink.

Index Terms—Microgrid, Flywheel Energy Storage System (FESS), Matlab/Simulink.

I INTRODUCTION

The worldwide is facing serious problems with electrical energy. From a side, the pollution caused by CO_2 emission from fossil fuels and from other side, the depletion of traditional sources like gas. Besides, the big losses, which are principally due both to the large electrical power produced in one place and long transmission lines.

To overcome these drawbacks, a new form of electricity generation has been proposed known as Microgrid. Usually, the latter is composed by an aggregation of distributed generation units, which depend essentially on renewable energy resources like wind and solar, loads and storage devices [1][2]. The whole system can be connected to either the main grid and known as grid-connected mode or works as autonomous known as standalone mode [3][4].

An important feature of renewable energy resources is the fluctuation of the output power over time. Hence, the importance of storage systems within Microgrid appears especially for boosting the power supplied by the Microgrid in grid-connected mode if the distributed generation sources are not supplying the expected level of energy due to their natural power variation [5].

Different types of storage exist, some are already used and others are under development and can be classified into two categories [6]:

a/- Long term storage: Where the period of storage is above 10 minutes and the well-known types of long term storage are batteries, storage under potential form of water.

b/- Short term storage: Where the period of storage is less than 10 minutes and well-known types of short term storage are Flywheel, super capacitor.

In this context, the objective of this article is to study the Flywheel Energy Storage System (FESS) alone: the latter has many advantages like: simple maintenance, detailed knowledge of stored energy level, clean storage unlike batteries, independent lifetime duration of storage/retrieval cycles.

This article is arranged as follows: Section II briefly describes the main component parts of the FESS and its working principle. In section III, the importance of such type of storage is presented. Section V is devoted to mathematical model of the whole system. The fifth Section shows the simulation results using Matlab/Simulink and discussion. Finally, conclusion is presented in Section VI.

II CONSTITUTION AND WORKING PRINCIPLE OF FLYWHEEL STORAGE SYSTEM

Figure 1 shows the main component parts of the storage system based on flywheel, which comprises the following elements:

- A flywheel
- A motor-generator
- A power electronic converter

As in the majority of the energy storage systems, there are a reversible transformation of energy. During storage, the electrical energy is converted into mechanical energy through the electric motor. The mechanical energy is stored in the flywheel as kinetic energy of a rotating mass. During the discharge of FESS, the mechanical energy is converted into electrical energy through the electric generator. The operating speed is imposed by the power electronic converter, which imposes the direction of transfer of energy through the electrical machine [6].

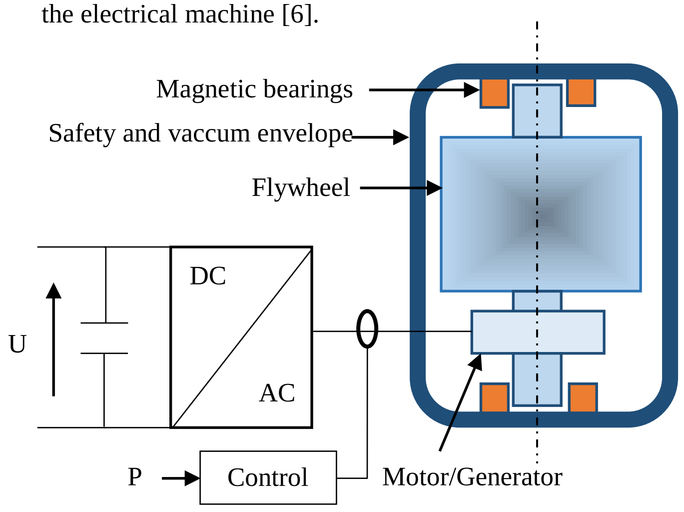

Figure 1: Flywheel Energy Storage System constitution [7]

U stands for dc voltage link.

III IMPORTANCE OF FLYWHEEL STORAGE SYSTEM

In order to illustrate the behavior of FESS in a Microgrid, we propose the schematic depicted in Figure 2 where the Microgrid in our case depend only on one type of renewable energy which is wind turbine connected to the grid in presence of a FESS.

We suppose that the wind profile enables to generate an active power P_{WIND}. The latter has variable values due to the random character of the wind. On the other hand, the grid must receive a smoothed power [6]. And knowing the power that must be delivered to the grid P_{reg}, the FESS reference power can be determined as follows:

$$P_{ref} = P_{reg} - P_{WIND} \quad (1)$$

If the reference power is positive, there is an excess of energy must be stored under kinetic form and the asynchronous machine works as motoring operation. Else, the asynchronous machine works as a generator where we have energy to deliver.

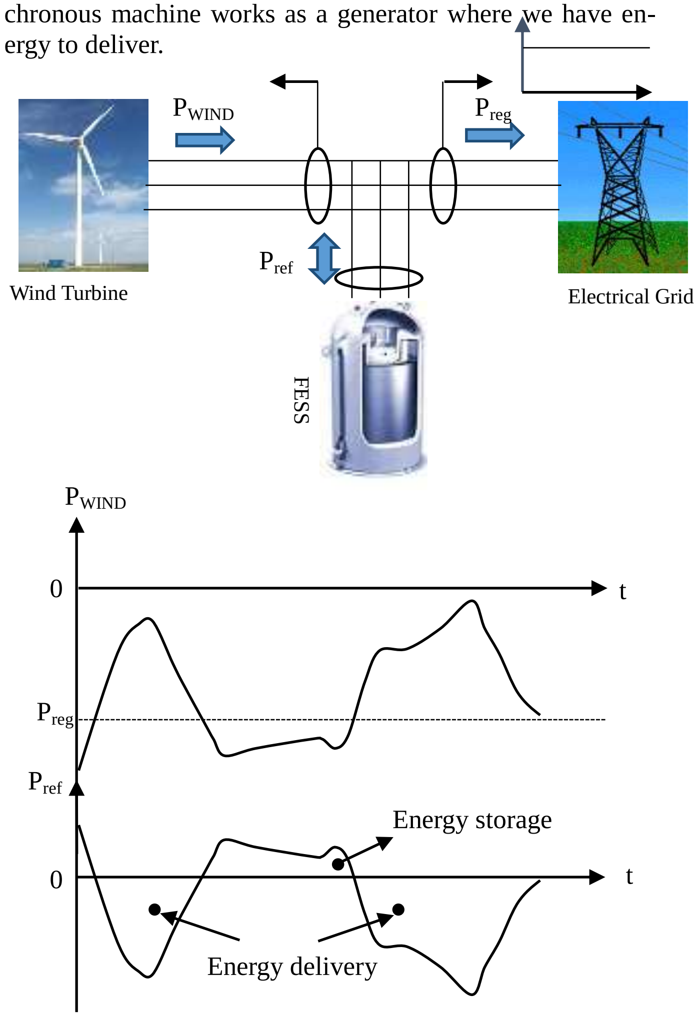

Figure 2 Example of Flywheel Energy Storage System associated

IV FLYWHEEL ENERGY STORAGE SYSTEM MODEL

In this part, the modeling of all parties constituting the FESS will be presented.

A Flywheel

In this paragraph, the value of the inertia of the flywheel according to the power storing and which can be restored in a timely manner will be determined. The relationship that related the power to energy is the following [8]:

$$P_F = \frac{dE_F}{dt} \quad (2)$$

With:

P_F: Maximum power deliverable by the storage system (equal to the nominal power of the asynchronous machine coupled to the flywheel) [W].

E_F: Energy stored [J].

Then, the relationship between energy, inertia and angular velocity is:

$$\frac{dE_F}{dt} = \frac{1}{2} J_F \frac{d\Omega_F^2}{dt} \quad (3)$$

Where:

Ω_F: Flywheel angular velocity in [rad/s].

J_F: Flywheel moment of inertia expressed in [kg.m^2].

The moment of inertia of the flywhell is a key parameter because it characterizes the ability of storage (or restitution). By grouping equations (2) and (3), we get the following equation:

$$P_F = \frac{1}{2} J_F \frac{d\Omega_F^2}{dt} \quad (4)$$

Passing to small changes, we have:

$$P_F = \frac{1}{2} J_F \frac{\Delta\Omega_F^2}{\Delta t} \quad (5)$$

Δt: Time variation during charge or discharge for maximum power [s].

$\Delta\Omega_F$: Small variation in angular velocity about an operating point, in [rad/s].

$$P_F \Delta t = \frac{1}{2} J_F \Delta\Omega_F^2 \quad (6)$$

$$J_F = \frac{2 P_F \Delta t}{\Delta\Omega_F^2} \quad (7)$$

$$J_F = \frac{2 P_F \Delta t}{\Omega_{Fmax}^2 - \Omega_{Fmin}^2} \quad (8)$$

Where:

Ω_{Fmax}: Maximum flywheel angular velocity in [rad/s].

Ω_{Fmin}: Minimum flywheel angular velocity in [rad/s].

B Asynchronous machine

The asynchronous machine is chosen according to these advantages in terms of simplicity and robustness of the rotating parts.

B.1 Electrical equations in the dq reference

We use the model of the MAS in the Park reference. Flux and currents are given by the following system [6][8][9]:

$$\frac{d}{dt}\begin{bmatrix}\phi_{dr}\\ \phi_{qr}\\ i_{ds}\\ i_{qs}\end{bmatrix} = \begin{bmatrix} \frac{-R_r}{L_r} & (\omega_s - p\Omega_F) & \frac{MR_r}{L_r} & 0 \\ (\omega_s - p\Omega_F) & \frac{-R_r}{L_r} & 0 & \frac{MR_r}{L_r} \\ \frac{MR_r}{\sigma L_s L_r^2} & \frac{Mp\Omega_F}{\sigma L_s L_r} & \frac{-R_{sr}}{\sigma L_s} & \omega_s \\ -\frac{Mp\Omega_F}{\sigma L_s L_r} & \frac{MR_r}{\sigma L_s L_r^2} & -\omega_s & \frac{-R_{sr}}{\sigma L_s} \end{bmatrix} \begin{bmatrix}\phi_{dr}\\ \phi_{qr}\\ i_{ds}\\ i_{qs}\end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} (9)$$

$$R_{sr} = R_s + \frac{M^2}{L_r^2} R_r \ (10)$$

$$\sigma = 1 - \frac{M^2}{L_s L_r}$$

$$\sigma = 1 - \frac{M^2}{L_s L_r} \ (11)$$

Where:

R_s, R_r: Stator and rotor phase resistances.

L_s, L_r: Stator and rotor phase inductances.

M: Mutual inductance.

v_{ds},v_{qs}: Direct and quadrature components of stator voltage.

i_{ds},i_{qs}: Direct and quadrature components of stator current.

ϕ_{ds}, ϕ_{qs}: Direct and quadrature components of the rotor flux.

p: Number of pole pairs.

ω_s: Pulsation of the field in the stator reference frame.

B.2 Control

To determine the control (reference voltages to be applied to the converter) of the asynchronous machine, we choose to work with rotor flux oriented control because equations are simpler compared to control stator flux or air gap flux oriented [6]. The positin of the reference is obtained to cancel the quadratic component of the flux rotor. Therefore, qlign the rotor flux vector with the axis of the Park reference.

Suppose:

$$\phi_{dr} = \phi \quad (12)$$
$$\phi_{qr} = 0 \quad (13)$$

We obtain the following equations:

$$\frac{d}{dt}\begin{bmatrix}\phi_{dr}\\ i_{ds}\\ i_{qs}\end{bmatrix} = \begin{bmatrix} \frac{-R_r}{L_r} & \frac{MR_r}{L_r} & 0 \\ \frac{MR_r}{\sigma L_s L_r^2} & \frac{-R_{sr}}{\sigma L_s} & \omega_s \\ \frac{-Mp\Omega_F}{\sigma L_s L_r} & -\omega_s & \frac{-R_{sr}}{\sigma L_s} \end{bmatrix} \begin{bmatrix}\phi_{dr}\\ i_{ds}\\ i_{qs}\end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} (14)$$

The reference flux is imposed by the field weakening law of the asynchronous machine as follows [6]:

$$\phi_{r-ref} = \begin{cases} \phi_{rn} & if\ |\Omega_F| \le \Omega_{Fn} \\ \phi_{rn} \frac{\Omega_{Fn}}{|\Omega_F|} & if\ |\Omega_F| > \Omega_{Fn} \end{cases} \quad (15)$$

Konowing that:

$$\phi_{rn} = \frac{L_r}{M}\,\phi_{sn} \quad (16)$$

ϕ_{rn}: Nominal rotoric flux [Web].
ϕ_{sn}: Nominal statoric flux [Web].
Where:

$$\phi_{sn} = \sqrt{3}\,\frac{v_s}{\omega_b} \quad (17)$$

With: v_s: Rms value of simple statoric voltage [V].
ω_s: Grid pulsation equal to 314.16 rad/s.
The reference direct statoric current is given by:

$$i_{ds-ref} = PI\big(\phi_{r-ref} - \phi_{r-est}\big) \quad (18)$$

PI: Proportienal integral regulator.
We estimate the value of rotoric flux through the following equation:

$$\phi_{dr-est} = \frac{M}{1 + \frac{L_r}{R_r}s}\, i_{ds} \quad (19)$$

s: Laplace operator.
We want to control the power of the asynchronous machine coupled to the flywheel. From a reference power, one can deduce the electromagnetic torque reference of the machine leading the flywheel by measuring the rotational speed. The expression of the electromagnetic torque can be calculated by [10]:

$$i_{qs-ref} = \frac{P_{Fref}}{\Omega_F} \quad (20)$$

C Converter

We define voltages modulated by the converter in the Park reference and applied to the stator of the asynchronous machine by the following system [9][11]:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \frac{U}{2}\begin{bmatrix} v_{d-reg} \\ v_{q-reg} \end{bmatrix} \quad (21)$$

With:
v_{d-reg} and v_{q-reg} represent converter adjusting tension in the Park reference.
As well, the current modulated by the converter is given by:

$$i_{m-mac} = \frac{1}{2}\,[v_{d-reg} \quad v_{q-reg}]\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \quad (22)$$

The control of the converter associated with the asynchronous machine is derived by reversing the system in Equation (21):

$$v_{d-reg} = \frac{2}{U}\, v_{ds-ref} \quad (23)$$

$$v_{q-reg} = \frac{2}{U}\, v_{qs-ref} \quad (24)$$

Knowing that:

$$v_{sd-ref} = E_{d-ref} - \frac{MR_r}{L_r^2}\,\phi_{r-ref} - \sigma L_s \omega . i_{qs-ref} \quad (25)$$

$$v_{sq-ref} = E_{q-ref} - \frac{Mp\Omega_F}{L_r}\,\phi_{r-ref} + \sigma L_s \omega . i_{ds-ref} \quad (26)$$

Figure (3): Flywhee

$$E_d = v_{ds} + \frac{M R_r}{L_r^2}\,\phi_{dr} + \sigma L_s \omega . i_{qs} \quad (27)$$

$$E_q = v_{qs} - \frac{Mp\Omega_F}{L_r}\,\phi_{dr} - \sigma L_s \omega . i_{ds} \quad (28)$$

$$E_{d-ref} = PI'\big(i_{ds-ref} - i_{ds}\big) \quad (29)$$

$$E_{q-ref} = PI'\big(i_{qs-ref} - i_{qs}\big) \quad (30)$$

And $$\omega = p\Omega_F + \frac{MR_r}{L_r}.\frac{i_{qs-ref}}{\phi_{r-ref}} \quad (31)$$

The globale FESS control scheme is depicted in Figure (3). Due to the large size of that scheme, it is placed at the end of this article.

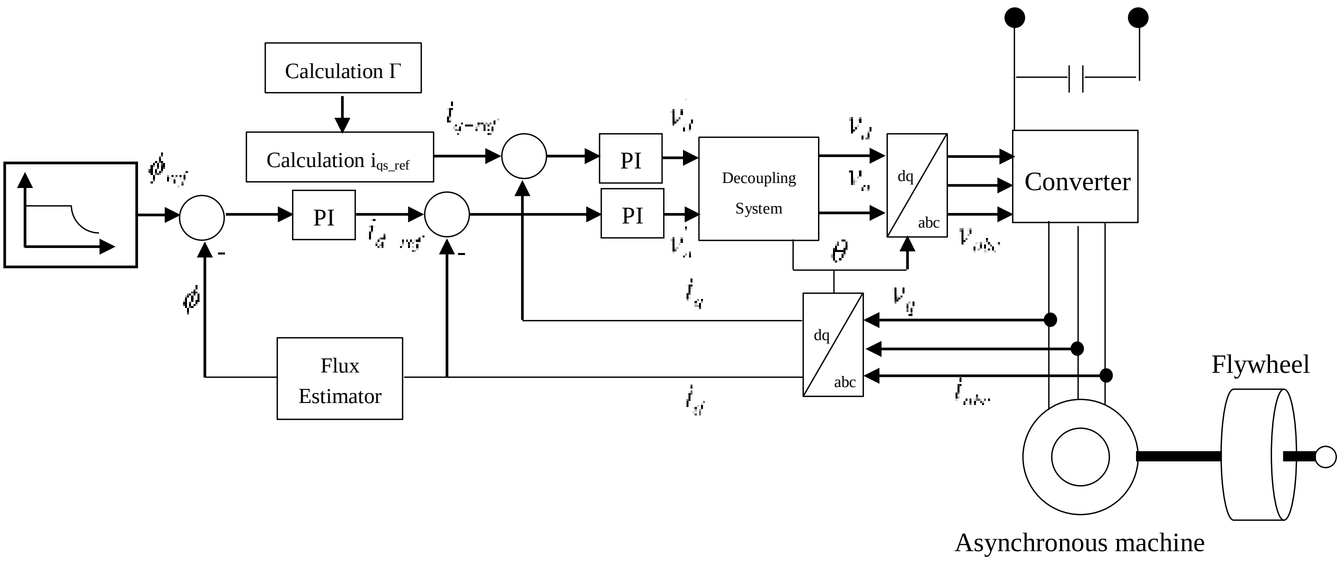

Figure (3): Flywheel Energy Storage System control [8]

V SIMULATION RESULTS

Figures (4) to (10) illustrate the operation of FESS in a period of 60 seconds. The initial velocity of the Flywheel is fixed at 1500 rpm and the reference power is equal to the nominal power of the asynchronous machine 450 kW.

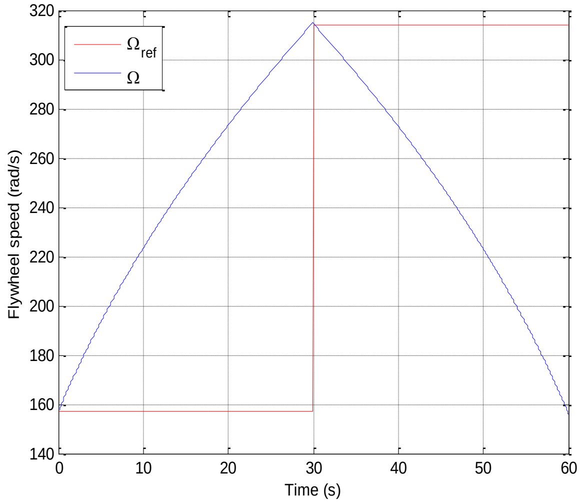

Figure (4): Flywheel rotation speed

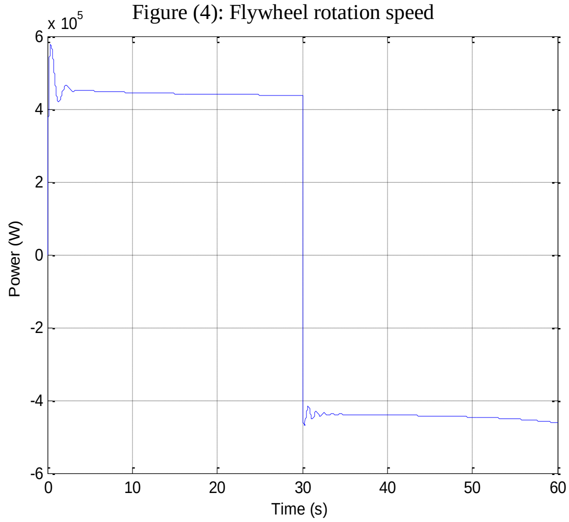

Figure (5): Power storage system

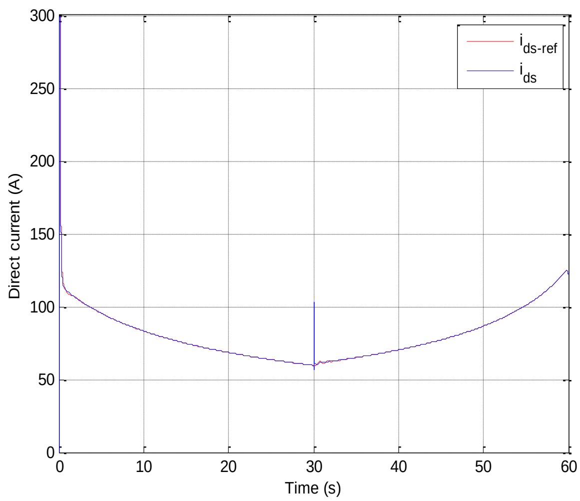

Figure (6): Direct statoric current

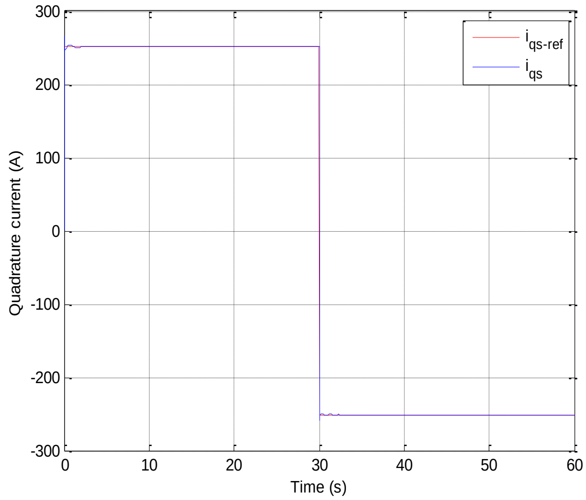

Figure (7): Quadrature statoric current

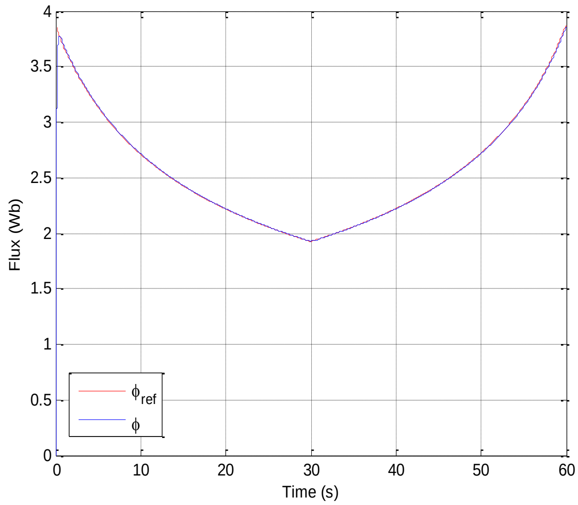

Figure (8): Rotoric flux

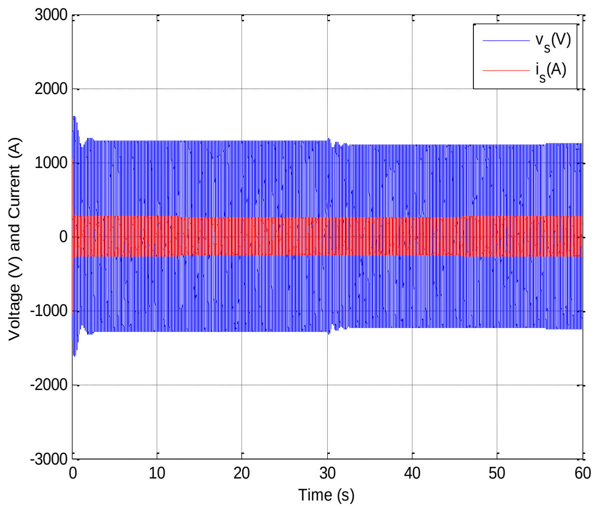

Figure (9): Statoric current and voltage

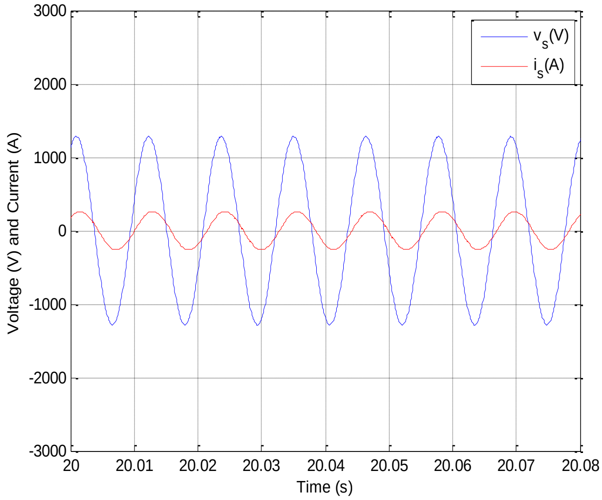

Figure (10): Zoom of statoric current and voltage during storage

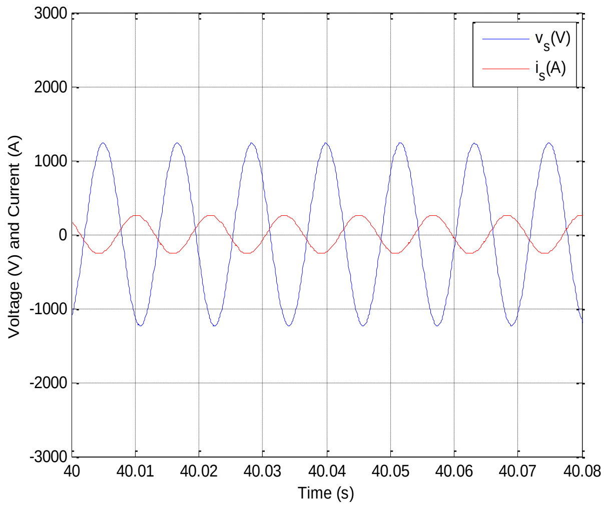

Figure (11): Zoom of statoric current and voltage during restitution

The flywheel rotation speed is shown in Figure (4). Note that the speed goes from 1500 to 3000 rpm in 30 seconds. This corresponds well to storage. Then this speed goes from 3000 to 1500 rpm in 30 seconds to restore 450 kW.

The power storage system is shown in Figure (5). It is requested in this simulation to store 450 kilowatts during the first 30 seconds and return 450 kW in 30 seconds remaining. Looking at this figure, we see that the reference power is followed.

We also note that the reference power is reversed when the speed of the flywheel reaches a high or low limit (see Figures 4 and 5).Therefore, we ask the asynchronous machine to provide or consume nominal power of 450 kilowatts. A positive power corresponds to a power consumed by the machine and a negative power represents a power supplied by the machine.

Figures (6), (7) and (8) respectively show the evolution of the direct, quadrature current and flux of the asynchronous machine, there is a good follow instruction.

A second observation that can be drawn from these figures depends on direct current and its relationship with the flux, it is found from the change in the direct current component, which is the image of the flux.

During storage, the current is in phase delay with the voltage where the machine acts as a motor (see Figure 10) and in return, the current is ahead of phase with the voltage where the machine works as a generator (see Figure 11) allows it to justify the two modes of operation of the asynchronous machine.

V CONCLUSION

In this article, we have presented the FESS as a solution to store electrical energy as a kinetic form in periods of excess of production of renewable energies sources and to restore it in the case of deficit following the random characteristic of such alternatives system.

Initially a general view of the constituent parts of this system and its operating principle has been shown. Then, each part of FESS have been modeled separately including: Flywheel, asynchronous machine and its control and power converter. Finally, the results using Matlab/Simulink software justify the advantages of the Flywheel Energy Storage System either in storage period where the system works as a motor and stocks 450 kW as a kinetic form or in restitution period where the system works as a generator.

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