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Control of a synchronous Generator Based on a Hybrid Excitation Connected to a Diode rectifier

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Abstract This project deals with the modeling and the control of the hybrid excitation synchronous machine (HESM) connected to a diode bridge rectifier. The set is operating as a DC generator that supplies an isolated grid in embedded applications such as aircraft electrical power generation. Saturation effects have also been taken into account. The aim of the control is to maintain the DC bus voltage constant when the load and/or the speed of the rotor vary. The hybrid excitation synchronous machine (HESM) combines the advantages of the two above-mentioned machines. As its name reveals, the excitation flux in this machine is produced by two different sources: the permanent magnets and a field winding that is placed at the stator to preserve a brushless structure. In the motor mode, the latter source is used to weaken the field in the air gap leading to a constant power operation over a wide range of speeds. In the generator mode, the electrical excitation allows the regulation of the output voltage under load and/or speed variation. Simulation results validate this approach.

Keywords— Synchronous generator, Hybrid excitation, Diode bridge rectifier, Control, embedded applications, aircraft.

INTRODUCTION

Permanent magnet machines are widely used in many applications due to their high efficiency and brushless structure. However, the excitation flux, produced by the permanent magnets, is hard to regulate once the machine is designed. Thus, the voltage regulation in generator mode and the speed increase in the motor mode are difficult to be realized. On another hand, rotor wounded synchronous machines offer good magnetic field regulation but their structure includes slip rings and brushes. In addition, they suffer from a low efficiency due to the losses in the excitation winding. The hybrid excitation synchronous machine (HESM) combines the advantages of the two above-mentioned machines. As its name reveals, the excitation flux in this machine is produced by two different sources: the permanent magnets and a field winding that is placed at the stator to preserve a brushless structure. In the motor mode, the latter source is used to weaken the field in the air gap leading to a constant power operation over a wide range of speeds. In the generator mode, the electrical excitation allows the regulation of the output voltage under load and/or speed variation.

The HESM were first investigated for their field weakening capability in motor mode. They provide an energy efficient solution for vehicles propulsion .

In generator mode, a parametrical study showed that it is possible to maximize the efficiency of the alternator at a given speed by choosing an adequate hybridization ratio .Previous papers treated the control of the HESM used in electrical generation systems for embedded applications, in particular aircraft power supplies. The grid supply is a DC bus. The machine is connected to a diode bridge rectifier or a PWM rectifier. The DC voltage is maintained constant through the regulation of the armature currents and the excitation current. The control is validated, by simulation and experiments, under -50% of load variation and ±20% of speed variation. In the present paper, a simpler control strategy for the HSEM debiting on a diode rectifier is proposed. The DC bus voltage is directly regulated via the unique action on the excitation current. The control is scalar and consists of just

two loops. No particular assumption is made on the stator currents. This new approach is evaluated by simulation under a wide range of load and speed variation. The following section is dedicated to the modeling of the DC generator. The model of the HESM is presented first. It is based on the conventional Park model of the machine. It is then improved by taking into account the saturation of the magnetic circuits in the machine. The modeling of the diode rectifier follows. In section III, the control of the DC voltage is detailed. The transfer function to be regulated is computed and a controller is synthesized. The transient characteristics of the output voltage are specified by MIL-STD-704F1. In section V, the control is validated by simulation under load variation (±50%) and speed variation (up to +400%) with Matlab/Simulink software.

II. Control

A. Control Strategy

The output of the DC generator is to be regulated. Since the converter considered in this paper is a diode rectifier, the generating system described above has only one degree of freedom: the voltage applied to the excitation winding. The control of the DC bus voltage is done through hierarchical loops:

an inner loop where the excitation current is driven by the voltage applied to the excitation winding and an outer loop that regulates the DC voltage by action on the excitation current (Fig. 3).

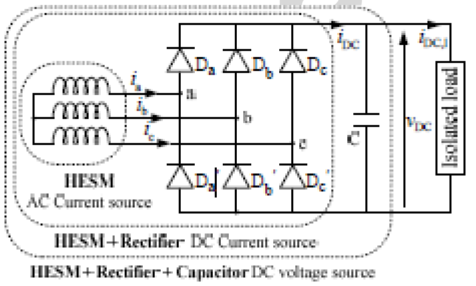

Fig.1 DC Voltage source

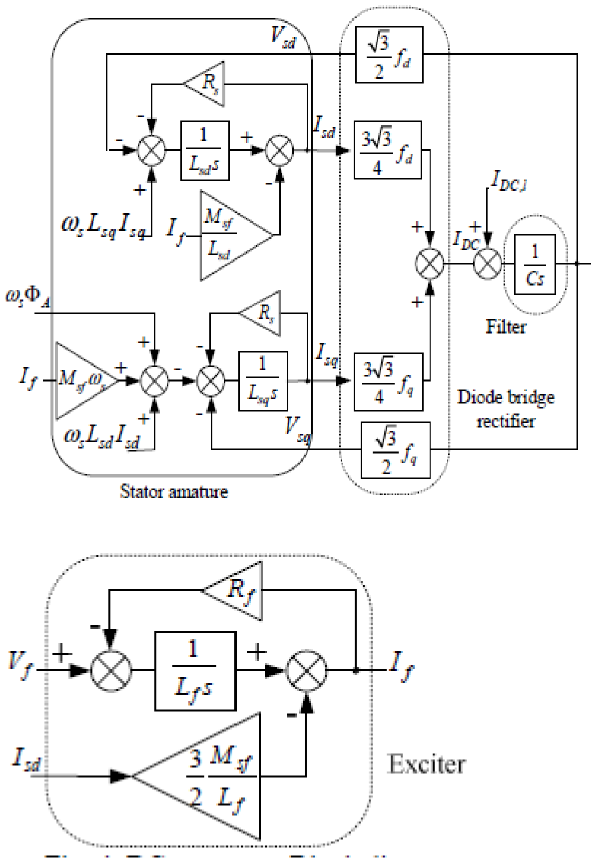

Fig.2 DC Generator block diagrams

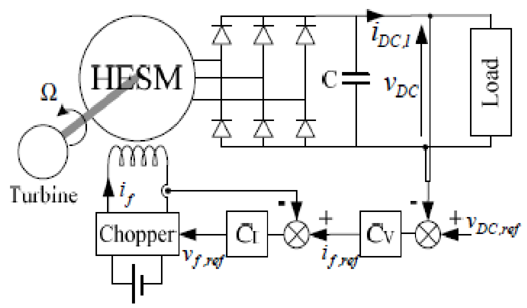

Fig.3 Control strategy of the dc generator

The inner controller C_1 a proportional-integral (PI), can be easily designed since the function to be regulated is a first order function (the term containing *i*sd is seen as a perturbation). The bandwidth of the inner closed loop is 150 rad/s.

B. Voltage controller design

The transfer function to be regulated is derived based on the block diagrams given in Fig. 2.

$$Gv(s) = V_{DC}(s) / If(s) = F_v(s)H_1(s)$$

$F_v(s) = V_{DC}(s) / If.ref(s) = (-3 \sqrt{3} / 4M_{sfb1}) / b_2+b_3$

With:

$b_1(s) = (f_d (L_{sqs}+R_s)s+f_{qp}\Omega(L_{sds}+R_s)),$

$b_2(s) = Cs(L_{sds}+Rs)(L_{sqs}+R_s)$ and

$b_3(s)= (9/8)(f^2d(L_{sqs}+Rs)+f^2q(L_{sds}+Rs)).$

H1(s) = 150/(s+150) represents the first order inner loop dynamic.

The outer loop controller is represented by the block diagram in Fig. 4.

The terms *fd* and *fq* are not constant. Fig. 5 shows the waveforms of *fd (t)* and *fq (t)* on a period of the stator current. Fig. 8 represents the poles and zeros map of the function GV(s)for 6 different values of (*fd(t)* , *fq*(*t*)). The dominant poles and zeros are almost the same for all these functions. Hence, in order to synthesize a controller, any value of (*fd*(t_0) , *fq*(t_0)).can be chosen from the waveform in Fig. 5. To simplify, let *fd* =0 and *fq* = -0.6667.

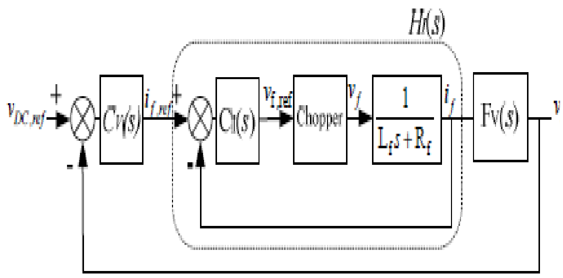

Fig.4 Block diagram of the voltage regulation

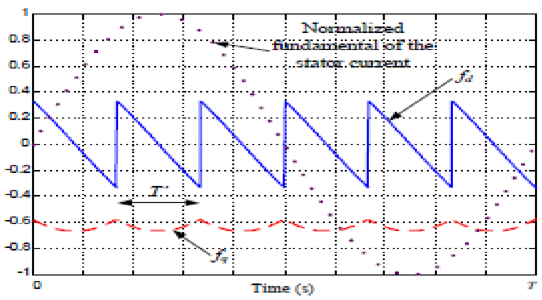

Fig.5 fd(t) and fd(t) waveforms on a period of the stator current

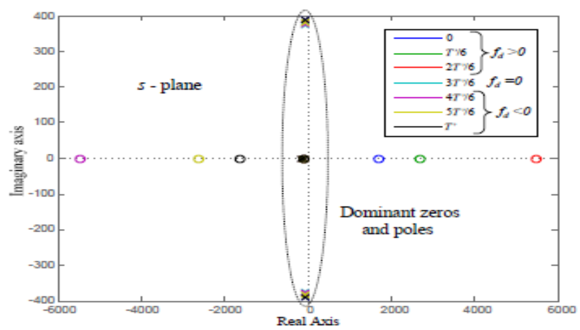

Fig.6 Poles and zeros map of Gv(s) for different values of (fd,fq)

The load doesn't explicitly appear in function *GV* (*s*) .However, it affects the values of the current in the stator windings and the needed excitation current. Since the inductances vary with these currents, due to the saturation of the magnetic circuits, then for each load corresponds a different function *GV* (*s*) .Fig. 9 represents some bode plots considered for different loads. In these plots, Ω= Ωb=2000 rpm. The saturation effect appears clearly when particularly *Msf* decreases due mainly to the increase of the excitation current in case of overload. Fig. 10 represents the bode plot of the function *GV* (*s*) and the corrected open loop transfer function for different rotor speeds at nominal load.

The stability margins of the unregulated open loop system are negative. Thus, the closed loop unregulated system is unstable. The HVDC is actually used in military aircraft platforms like F-22 or F-35 [14]. Thus, the output DC voltage should comply with the MIL-STD-704F guidelines. Given the transient envelopes of the DC bus voltage as specified by this standard, the required transient characteristics of the output voltage is determined and a PI controller, *CV*, is synthesized. The regulated system is stable for the considered speed and load range. The phase and gain margins are drawn on Fig. 7 and Fig. 8 for the nominal load and the base speed: *ΔG*=11dB,

$\Delta\Phi$=84°. The bandwidth in this case is 30 rad/s.

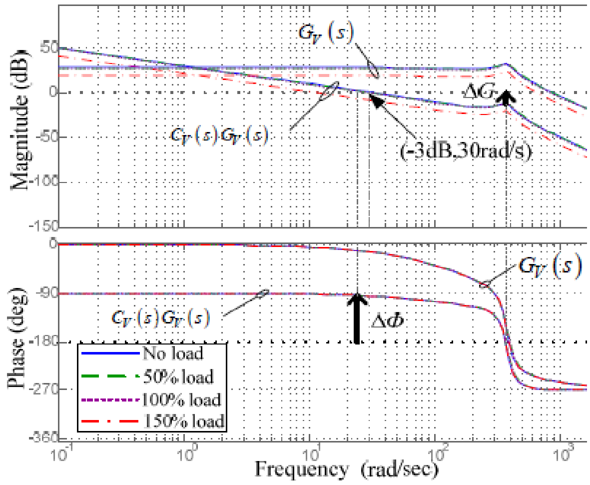

Fig.7 Bode plots of Gv(s) and Cv(s) Gv(s) for different loads

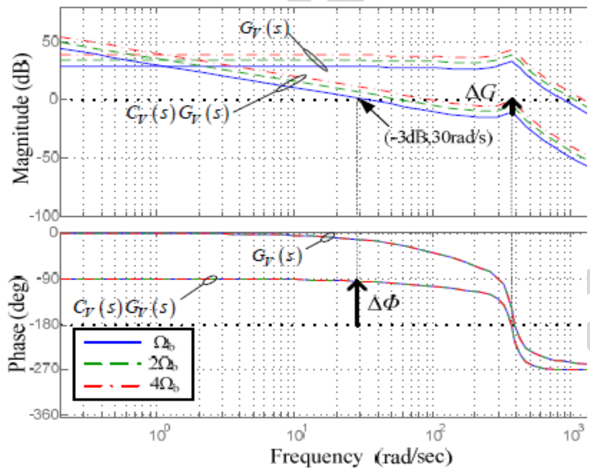

Fig.8 Bode plots of Gv(s) and Cv(s) Gv(s) for different rotor speeds

III. SIMULATION CIRCUITS

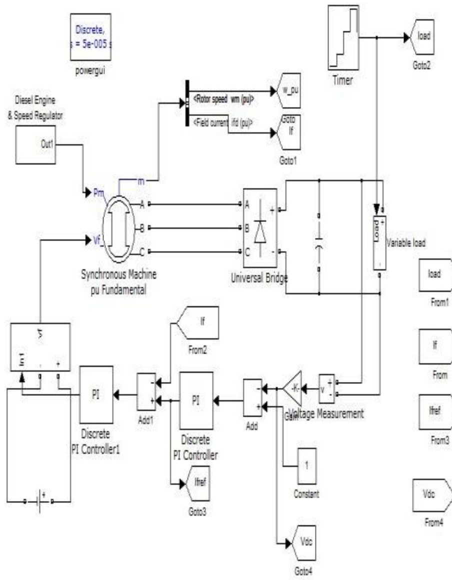

Fig. 9 Circuit for load variation

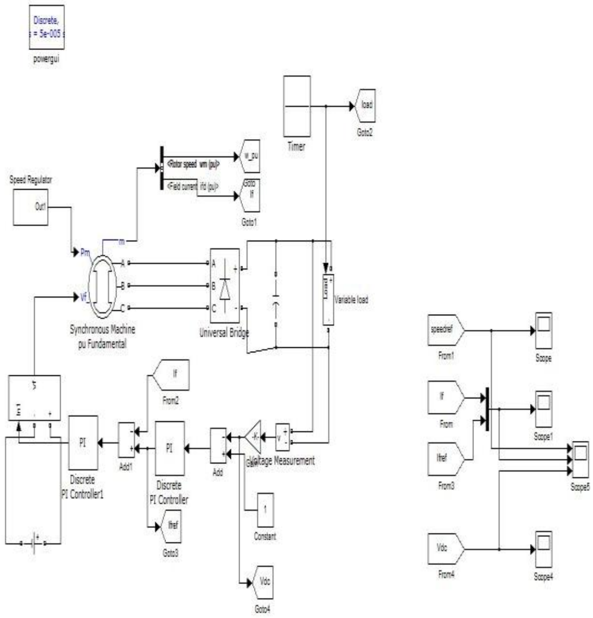

Fig.10 Circuit for speed variation

Output waveforms under load variation

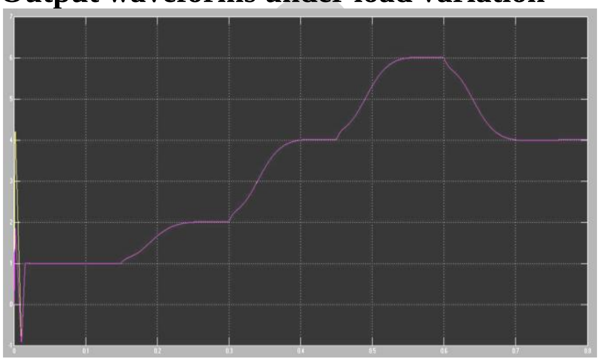

Fig.11 Excitation current in (amp)

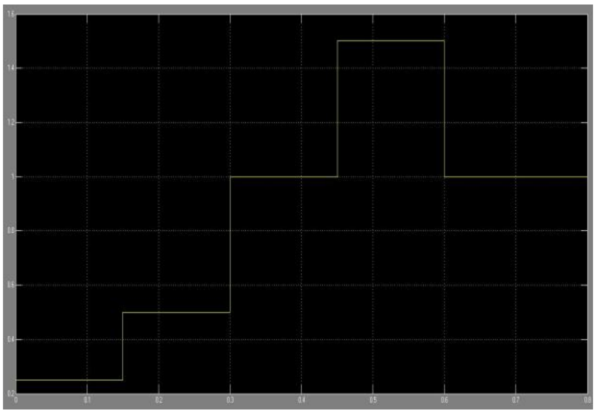

Fig.12 Load voltage in (pu)

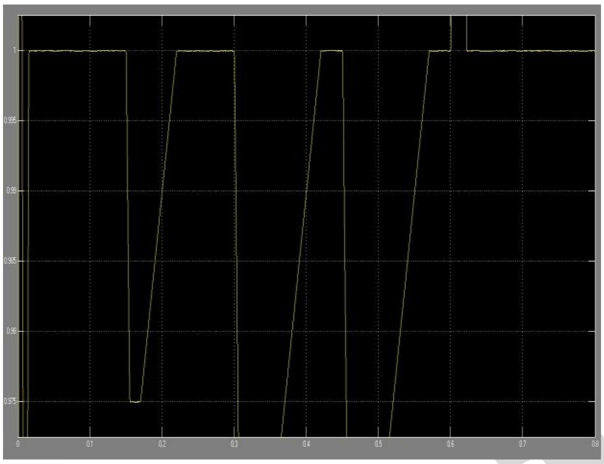

Fig.13 Dc output voltage(volts)

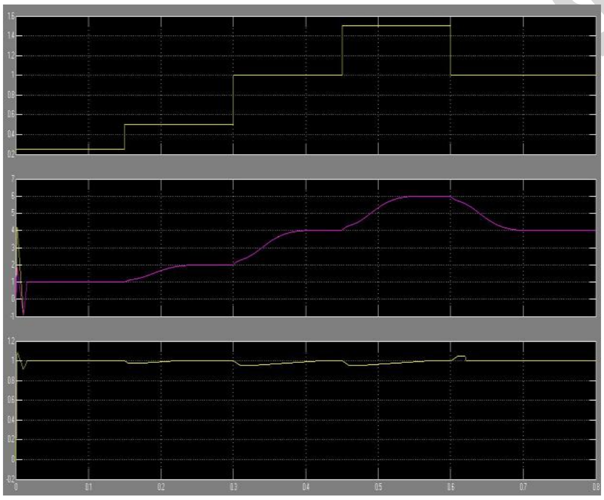

Fig.14 Simulation results under load variation

Output waveforms under speed variation

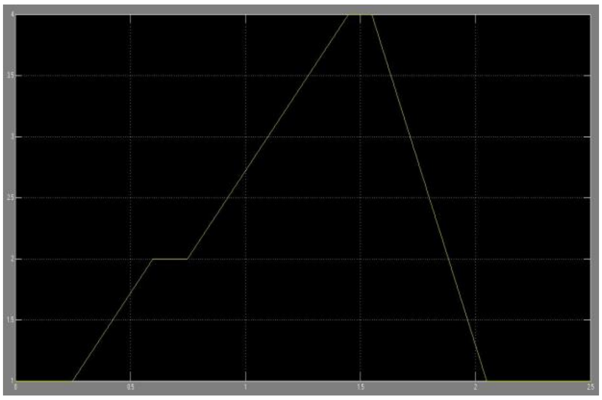

Fig.15 Rotor speed

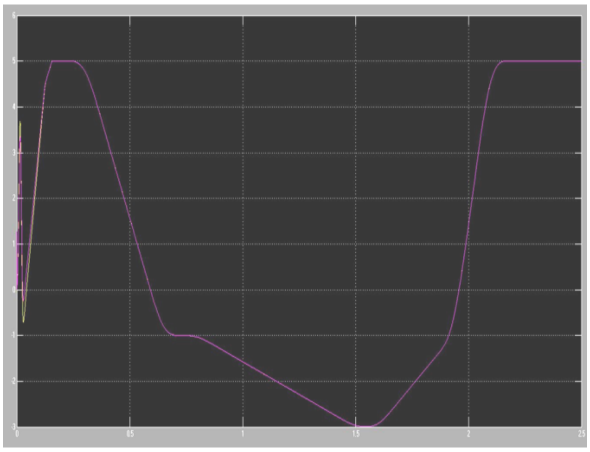

Fig.16 Excitation current (Amp)

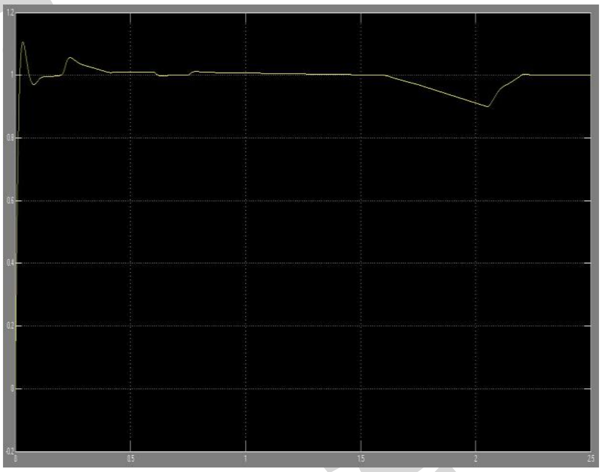

Fig.17 Dc voltage

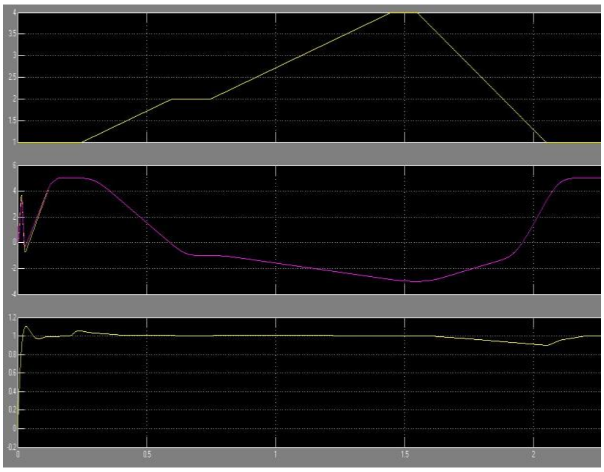

Fig.18 **Simulation results under speed variation**

HESM PARAMETERS

p	Number of pair of poles	6
P_n	Rated power	2500 W
Ω_b	Base speed	2000 rpm
R_s	Stator winding resistance per phase	0.76 Ω
R_f	Excitation winding resistance	1.35 Ω
L_{sd}	*d*-axis stator inductance	6.86 mH
L_{sq}	*q*-axis stator inductance	8.91 mH
L_f	Excitation winding inductance	75 mH
M_{sf}	Mutual inductance stator/ inductor	12.68mH
Φ_M	Maximum value of the flux produced by the permanent magnet in a stator winding	121 mWb

CONCLUSION

The model of the machine is first elaborated. This model takes into consideration the saturation of the magnetic circuits. The diode bridge rectifier modeling follows. Then the DC bus voltage regulation is studied. With one degree of freedom, the control consists of only two loops: excitation current controller (inner loop) and DC voltage controller (outer loop). Simulation results prove the capability of the generator to operate correctly under a wide range of load or speed variation (up to 4 times the base speed). The DC bus voltage remained, in both cases, within the limits imposed by the MIL-STD-704F.

New trends in aircraft power systems consider the HVDC distribution network. This paper presents the HESM, a compact brushless machine, associated to a diode bridge rectifier, to be used as a stand-alone DC generator in aircraft power supply systems. The HESM is a potential candidate to substitute the complex structure based on three machines, presently in use in aircraft electrical power generation.

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