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HALL THRUSTER DIRECT-DRIVE ASSESSMENT AND DEMONSTRATION

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Abstract

This thesis presents a theoretical and experimental study of the Hall thruster Direct-Drive configuration: an innovative way to deliver power to electric thrusters and a candidate for future spacecraft's propulsion system architecture. The direct connection between the solar array and the Hall thruster allows a drastic simplification of the Power Processing Unit (PPU) of the propulsion system. This has an immediate impact also on the thermal control system (TCS) which can be consequently lightened. Further mass benefits can be obtained in other subsystems of the spacecraft such as the electric power system.

The work is mainly divided in two parts. The first one assesses, in terms of mass reduction, the impact that the Direct-Drive configuration entails in the spacecraft subsystems; different kinds of space missions are considered, with different level of Hall Effect thruster power. Although the mass advantages that the Direct-Drive can afford are mission dependent, it has been proved that as the thruster and spacecraft power increase also the mass benefits become larger.

The second part of thesis concerns an experimental demonstration of a Direct-Drive system supplying the Alta's HT-100, a low power Hall thruster. The test required the procurement of the solar panel and the design of an electrical filter. By means of simulations with Pspice software and experimental tests, a LC filter was developed and then arranged between the solar array and the thruster in order to dampen the current oscillations. This test successfully proved the correct ignition and the thruster operations up to 370 W of discharge power, representing in this way the first accomplished attempt in Europe of a Direct-Drive application.

Sommario

Questa tesi si occupa dello studio teorico e sperimentale della configurazione *Direct-Drive* per i motori ad effetto Hall: un modo innovativo di fornire potenza ai propulsori elettrici e candidata per futuri sistemi propulsivi di veicoli spaziali. La connessione diretta tra i pannelli solari e il motore Hall permette una drastica semplificazione dell'unità di processo della potenza del sistema propulsivo. Questo ha un impatto immediato anche nel sistema di controllo termico che può essere di conseguenza alleggerito. Inoltre, ulteriori benefici di massa possono essere ottenuti in altre parti del veicolo spaziale come per esempio nel sistema elettrico di potenza.

Il lavoro è principalmente diviso in due parti. Nella prima parte si è valutato in termini di riduzione di massa l'impatto che la configurazione *Direct-Drive* comporta nei sistemi del veicolo spaziale; sono stati analizzati differenti tipi di missione con motori Hall con diversi livelli di potenza. Nonostante i vantaggi di massa dipendano dal tipo di missione, si è dimostrato che in generale all'aumentare della potenza del motore e del veicolo anche i benefici di massa crescono.

La seconda parte della tesi riguarda una dimostrazione sperimentale di un sistema *Direct-Drive* che ha alimentato il propulsore HT-100, un motore di bassa potenza sviluppato ad Alta. Il test ha richiesto l'approvvigionamento di pannelli solari e il progetto di un filtro elettrico. Mediante simulazioni con il software Pspice e test sperimentali, è stato sviluppato un filtro LC che poi è stato interposto tra il motore e il pannello solare per smorzare le oscillazioni di corrente. Questo test ha dimostrato con successo il corretto funzionamento del motore fino ad una potenza di scarica di 370 W, rappresentando in questo modo il primo tentativo riuscito in Europa di una dimostrazione *Direct-Drive*.

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Nomenclature

A = Area, m^2
AM = Available Module
B = Magnetic Field, T
C = Capacitance, F
CSE = Chopper Stage Efficiency
CSM = Chopper Stage Mass, kg
$CSPO$ = Chopper Stage Power Input, kW
$CSVI$ = Chopper Stage Voltage Input, V
E = Electric Field, N/C
e = Elementary Charge, C
FSE = Filter Stage Efficiency
FSM = Filter Stage Mass, kg
$FSPO$ = Filter Stage Power, kW
$FSRF$ = Filter Stage Ripple Factor
$FSVO$ = Filter Stage Voltage Input, V
f = Frequency, 1/s
f_I = Current Loss Coefficient
f_V = Voltage Loss Coefficient
G = Irradiance, W/m^2
g_0 = Gravitational Acceleration, m/s^2
I = Current, A
I_{sp} = Specific Impulse, s
$ITSE$ = Inverter Transformer Stage Efficiency
$ITSM$ = Inverter Transformer Stage Mass, kg
$ITSPO$ = Inverter Transformer Stage Power, kW
$ITSVI$ = Inverter Transformer Stage Voltage Input, V
$ITSVO$ = Inverter Transformer Stage Voltage Output, V
L = Characteristic Lenght, m
L = Inductance, H
L_d = Life Degradation

L_i = Ionization Mean Free Path, m
l = Magnetized Plasma Thickness, m
m = Electron Mass, kg
$\dot{m}$ = Mass Flow Rate, kg/s
M = Mass, kg
n = Number Density, $1/m^3$
N = Number of Sample
N_v = Avogadro’s number
P = Power, W
R = Resistance, Ω
$\dot{R}$ = Erosion Rate, m/s
RM = Required Module
RSE = Rectifier Stage Efficiency
RSM = Rectifier Stage Mass, kg
$RSPO$ = Rectifier Stage Power, kW
$RSVI$ = Rectifier Stage Voltage Input, V
r_L = Larmor Radius, m
SF = Switching Frequency, 1/s
$s.e.$ = Specific Energy Density, Whr/kg
t = Time, s
T = Temperature, °K
T = Thrust, N
T = Period, s
T_c = Solar Cell Temperature, °K
V = Voltage or Potential, V
v = Velocity, m/s
v_e = Exhaust Velocity, m/s
W = Atomic Weight, kg
w = Plasma Width, m
Y = Sputtering Yield of the Material
β = Hall Parameter
β_{Ipp} = Temperature Coefficient for Current at Peak Power Point, 1/°C
β_{Isc} = Temperature Coefficient for Current at Short Circuit Condition,1/°C
β_{Vpp} = Temperature Coefficient for Voltage at Peak Power Point, 1/°C
β_{Voc} = Temperature Coefficient for Voltage at Open Circuit Condition,1/°C

Γ = Flux, 1 / (m^{2}s)
ε = Loss factor
ε_i = Ionization Loss factor
ΔV = Delta-V, m/s
η = Efficiency
η_i = Current Efficiency
ν = Collision Frequency, 1/s
ρ = Density, kg/m^3
σ = Collision Cross Section, m^2
ω_C = Cyclotron Frequency, 1/s

Subscripts and Superscripts

a = Anode
A = Acceleration
A.C. = Attitude Control
av = Avarage
C = Coupling
Cg = Cathode-to-Ground
b = Beam
d = Discharge
D = Daylight
e = Electron
ea = Electron Arriving at Anode
ec = Electron Arriving at Cathode
E = Eclipse
E_i = Ionization Energy
eV = Electron-Volt
H = Hall
H.V = High Voltage
i = Ion
ia = Ion Arriving at Anode
ic = Ion Arriving at Cathode
L.V = Low Voltage

m = Propellant Usage
n = Neutron
OC = Open Circuit
p,P = Propellant
PP = Peak Power
r = Radial Direction
RMS = Root Mean Square
s = Series
sa = Solar Array
sav = Saved
sh = Shunt
SC = Short Circuit
T = Thrust
TE = Transmission
t =Thruster
th = Thermal
v = Spread Velocity
w = Wall
z = Axial Direction
β = Focusing
ε = Acceleration

In the case of identical symbols the context of their mention will make the meaning completely clear.

Acronyms

ABM	Analogue Behavior Modeling
AC	Alternating Current
ACS	Attitude Control System
BOL	Beginning Of Life
DC	Direct Current
DOD	Depth of Discharge
DET	Direct Energy Transfer
DDU	Direct-Drive Unit
EM	Engineering Model
EMI	Electromagnetic Interference
EOL	End of Life
EOR	Electric Orbit Raising
EPS	Electric Propulsion System
FFT	Fast Fourier Transform
FU	Filter Unit
GEO	Geostationary Earth Orbit
GTO	Geostationary Transfer Orbit
GPS	Global Positioning System
GSD	Ground Sample Distance
HKM	Heater Kathode Magnet
HET	Hall Effect Thruster
LAE	Liquid Apogee Engine
LEO	Low Earth Orbit
NEA	Near Earth Asteroid
NSSK	North-South Station Keeping
PMAD	Power Management and Distribution
PPU	Power Processing Unit
PV	Photovoltaic
PWL	Piecewise Linear
PWM	Pulse-Width Modulation

S/C	Spacecraft
SPT	Stationary Plasma Thruster
RMS	Root Mean Square
TAL	Thruster with Anode Layer
TCS	Thermal Control System
TSU	Thruster Switching Unit
TWTA	Travelling Wave Tube Amplifier
XFC	Xenon Flow Controller

Introduction

Since the early sixties, when the Hall Effect thruster started to be developed both in United States and Soviet Union, it was already clear that this kind of engines, and in general all the electric thrusters, could have ensured large propellant savings with respect to the chemical thrusters. In fact, since the atoms accelerated through the chamber reach exhaust velocity about one order of magnitude higher than in the case of chemical thrusters, this leads to a reduction of the propellant needed for the same velocity change (to the detriment of a longer thrust period). After the launch in 1971 of the first Soviet Hall thruster (SPT-50) the interest and the use of this type of devices increased, first in Russia and then in the Western world since the nineties.

The discharge voltage required by the Hall thruster is in the order of 300 V, but the energy produced by the solar array is generally characterized by a lower voltage (e.g. 28 V, 50 V). Therefore, a Power Processing Unit (PPU) is interposed between the thruster and the solar array in order to step up the voltage and to manage the thruster functions. The removal of the DC-DC converter (anode supply) dedicated to the thruster discharge involves a significant simplification of the PPU. Thus, the Direct-Drive configuration proposes to directly connect the solar array, arranged for producing power at 300 V, to the thruster. Even if there are some technological issues to overcome (e.g. avoid arcing in the solar array), this simplification involves direct benefits not only in the PPU but also in its Thermal Control System (TCS). Indirect advantages can also be exploited by the implementation of high voltage bus, in fact this configuration allows to improve the electrical power system efficiency and thus to reduce its overall mass.

The idea of the Direct-Drive was born in the early seventies in NASA laboratories [58] in relation to the ion thrusters. *"For large electrical loads such as ion thruster and high-power radio frequency amplifiers, the necessary power processors are heavy, complex, and expensive to design and build and are a substantial burden on the spacecraft thermal control system"* stated Gooder in 1977. As said, the opportunity to simplify and then lighten the power processor of the electric propulsion system was and is still now a very attractive opportunity for space missions.

The Comet Halley rendezvous which would be occurred in 1986 pushed the engineers to study a feasible mission strategy with solar electric propulsion; the NASA's 30-cmdiameter gridded ion thruster, directly supplied by a solar array, was a real candidate for such a mission. The task revealed too much demanding for the state-of-the-art technology, however the first experimental tests of a Direct-Drive configuration were fulfilled. The ion thruster was correctly operated at a discharge supply up to 1 A at a beam voltage of 1100 V, the solar array was placed indoor and illuminated with a set of lamps. Gooder highlighted that the tests were successfully accomplished and no issues were detected in thruster operations; in parallel, some studied involving plasma interactions in high voltage solar array were carried out.

After the desertion of the comet Halley mission, in the 1980s the interest in Direct-Drive waned, also because the possibility to develop reliable space solar array, capable to produce more than 1000 V for ion thruster, seemed to be very remote.

But in the first years of the nineties, after the confirmation of the Russian Hall thruster performance, the attention toward the Direct-Drive revived. As already outlined, the Hall thruster needs a discharge voltage of about 300 V; this entails the use of a much more manageable solar array than in the case of the ion thruster.

First in 1997, Hamley et al. [25] tested the 4.5 kW T-160 Hall thruster directly driven by a 1 kW linear concentrator terrestrial solar array placed outdoor. The thruster, firing up to 1 kW at 200 V and 780 W at 300 V, correctly operated during start up and steady state phases.

In 2001, NASA undertook the Direct-Drive Hall Effect Thruster (D2HET) program whose scope was to understand and overcome the issues related to the Direct-Drive implementation. System studies were carried out and the interactions in high voltage solar array immersed in a plasma environment were investigated.

In 2009, the first test using triple junction solar cells is documented. In this case Brandhorst et al. [8] employed a 1.2 kW stretched-lens concentrator solar array to supply the Russian 1.3 kW T-100 Hall thruster. The results proved that the thruster successfully worked up to 600 W and 550 V.

The current interest in high-power solar electric propulsion for human missions toward near-Earth asteroids [9] makes the Direct-Drive concept a natural option for such missions. In this context, NASA decided (in 2011) to set up at JPL an 11 kW solar array test-bed constituted by mono-crystalline silicon cells. A dedicated power control station ensures flexibility of the array performance by varying the series-parallel configuration of the solar panels. In 2012, at JPL, the most extensive and detailed Direct-Drive experimental investigation [58] was carried out in order to understand the several issues identified in previous tests. The Hall thruster utilized was the American H6, capable to reach a discharge power up to 12 kW. The experimental campaign involved the examination of thruster operations in various portions of the solar array I-V curve, different procedures of start-up and shut-down were analyzed and then, also how filter capacitance affects the system oscillations was studied. The thruster correctly operated up to 10 kW and a lot of useful answers came out from these tests.

Arising from the above literature, this thesis has the scope to assess in terms of mass reduction the Direct-Drive implementation impact in spacecraft systems and then, to experimentally demonstrate that the Alta’s HT-100 low power Hall Effect thruster can be effectively supplied by a solar array (in particular a set of thin-film amorphous silicon solar panels capable to provide up to 370 W).

The first part of the thesis is related to the assessment of the Direct-Drive effects on the spacecraft systems; after a brief description of Hall thruster principles of operation (chapter 1), it is illustrated the standard Power Processing Unit (PPU) architecture (chapter 2) and in particular the discharge supply which is its most significant element in terms of mass, inefficiency and complexity. Then, the chapter 3 explains in detail what is and which advantages can be exploited by the Direct-Drive implementation; the mass advantages are subdivided in direct and indirect referring to the ones attainable as a direct consequence of the Direct-Drive and the ones that can be exploited by the adoption of solutions strictly related to the Direct-Drive (e.g. the high voltage bus); in this chapter, also the issues related to such a configuration are qualitatively analyzed. The following chapters (4, 5, 6 and 7) quantitatively assess the mass benefits that the Direct-Drive would afford if implemented in existing (or existed) missions propelled by respectively low (less than 1 kW), medium (1-2 kW) , high (in the order of 5 kW) and very high-power Hall thrusters (more than 10 kW). Here, a remark must be made: the Hall thrusters’ subdivision in terms of power level depends on the current state-of-the-art. In the medium-brief term, this classification will be probably obsolete and the development of very high-power thruster (only prototypes to date) will have an influence also in the subdivision. For instance, nowadays a 5 kW thruster belongs to the class of high-power, in fact there are only one operative mission (AEHF) propelled by Hall thrusters in this range of power. In the next years, this thruster will be probably classified as medium-power thruster and, as the 10 kW (or more) thruster will become more common, they will belong to the high-power category. The chapter 8 shows the conclusions inferred by the analysis of the previous chapters.

The second part of the thesis is related to the Direct-Drive demonstration for the Alta’s HT-100 low-power thruster. The list of the devices, facilities and instrumentation employed in the experimental test is displayed in the chapter 9. Then, in the chapter 10, the steps toward the filter design are shown: circuit simulations with Pspice software and HT-100 tests with laboratory power supply were carried out in order to achieve satisfactory filter performance. The chapter 11 describes the effort in understanding and evaluating the influence of several factors such as the solar irradiance, cells temperature, and losses, involved in the solar array output performance. The chapter 12 illustrates the procedure and the results of the experimental test which has successfully demonstrate the HT-100 Direct-Drive operations. Finally the chapter 13 explains the conclusions derived from the experience of this work.