AN OPERATION OPTIMIZING FOR BOTH ELECTRIC POWER
AND PROPULSION SYSTEMS EQUIPPED WITH STATIONARY
PLASMA THRUSTERS

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Introduction

Mode varying and throttling of the electric propulsion system (EF-system) with
Stationary Plasma Thrusters (SPT) are presented in this paper. A mode varying
of Primary Power System (PPS) under mission conditions is conducive to search
control procedures for SPT based on the quasi-stationary thruster mode (pulse
mode). It is possible according to dynamic performances studying with the
thruster arc in the discharge circuit. A similar procedure may be applied to
the thruster when an unstabilizing High Voltage Power Processor (HVPP) can be
used for the discharge supply.

In the second part of the paper is tried simulating of the deep throttling
subsystem in the solar batteries failure.

Quasi-stationary discharge mode of SPT

It is known that repeated attempts were made for SPT deep throttling by the
pulse injection of the gas propellant into discharge chamber as named Quasi-
Stationary Plasma Thruster (RSPT) [1]. A result of this research was the
development of RSPT with 5-cm av. diameter. But some serious defects took
place in the operation principle. First of all a cyclical heating of the
thruster elements was observed. A thermo-mechano destruction of both dielectric
chamber and cathode [2] depended with mentioned heating decreased the life-
time of thruster. Than propellant leakages under protracted pulse fronts and
lost power must be taken into account. Moreover, pulse frequencies more than 4
Hz were impracticable.

The presented method of SPT regulating is the attempt to pass over these
problems. It base on the pulse discharge voltage application The anode voltage
was formed as:

\[ U_d(t) = U_{do} + U_{dh}(t) \]

The \( U_{dh}(t) \) was generated as the voltage pulses added to the constant
voltage level \( U_{do} \). The pulse frequencies were in a range \([f_1, f_2]\). The lowest
frequency \( f_1 \) of the range was selected according to a possibility of the gas
flow into the ionization zone for the filling. The effective value of length
\( L_i \) of the ionization zone can be estimated as function according to the ioniz-
ation phenomena [3] as:

\[ L_i = \frac{2eE\nu_{ao}}{X_a \beta \frac{M_e}{q_0} \frac{M_p^{\frac{2}{2}}}{q_0^{\frac{2}{2}}}} \]

(1)

Here, \( \beta = b(T_e, A) \) is the ionization coefficient related with the propellant
kind \( A \) and electron energy \( T_e; M_e \) - atomic weight and electric intensity; \( \nu_{ao} \)
- atom/ion flow velocity near anode; \( X_a \) - constants.

The detail count in Ref.[3] based on the kinetic equations had confirmed
the estimation (1). So, the pulse frequencies boundaries can be define as:

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The longitudinal velocity $V_{0}$ of the non-accelerated flow was the function of the atom temperature $T_{a}$, atom-ion density $n$ near the anode-distributor. The highest frequency boundary can be estimated using by the response time $t$: of current and voltage in the discharge circuit.

The pulse-amplitude-modulation (PAM) and pulse-length-modulation (PLM) can be realized using the discharge pulse operation mode. The thruster throttling can be fulfilled deeply with discharge PAM, PLM. It is the vital problem for the power processor break down. In this case the pulse width $T_{i}$ can not be less than $t$ value. The $T_{i}$ time must provide the operation heating level for the emission surface of cathode or the cathode must be heat up by the inside heater.

The $T_{i}$ value was important for the thrust performance. There was the extreme frequency value $f_{\text{ext}}$ corresponded to the best filling by the propellant gas flow of the ionizat ion area of the thruster chamber. The value was found according to the extreme level of the quasi-state experimental thrust level (Fig. 1).

SPT quasi-state (pulse) operation

The presented pulse mode was tested on 76-mm average diameter SPT-76 series.

There was the control discharge power processor the thruster arc, the pulse modulator and the current sensor in the SPT discharge circuit. The cylindrical probe was used for the beam plasma oscillations indication. The thrust level $F$ was measured by the torsion balance. The thrust variable as functions of the pulse width, $T_{i}$, pulse frequency $f$, amplitude $U_{d0}$ can be seen Fig. 2.

Ionization instability phenomena was investigated in the $f$ range $2.5<f<10$ KHz. The average thrust decreasing or the arc break were the effects of that phenomena. These characteristics corresponded to the dynamic performances of the discharge electrical circuit components.

A pulse width minimum for the arc break was observed. After that, the arc was ignited by the cathode heater.

However, the frequency response showed that the instability phenomena was actuated for $f=65...85$ KHz. Probably, these oscillations were corresponded to instability in higher frequencies than ionizat ion ones. In this case, the decrease of thrust level was not observed. Typical time & frequency responses are shown in Fig. 3.

So as the result of the quasi-state mode researches the conclusion was done that mode has advantages over QSP with its low frequency pulse feed propellant, because of absence the thermo-mechanodestruction, the quick control response of the thrust level, a possibility to choose optimal pulse frequencies took place. And we can see that obvious defect is the stimulation of high frequency modes (more 1 MHz) in the discharge circuit, but not in plasma beam for measurements by probes on the distance 20 cm from SPT chamber butt end.

Discharge admittance consideration

A possible approach to the phenomenon estimation of the discharge admittance for the SPT was presented by author in Ref [4].

Generally, the method of the dynamic system analyze was based on the kinematics equation linearized (transfer functions) of blocks that caused the mechanistic approach to the design of discharge admittance models. These admittance transfer functions were attached near several operation points of
SPT where the experimental linear performances can be obtained by the analysis of the discharge voltage/current fluctuations.

Using and mentioned assumptions to the arc admittance transfer function structure the result can be defined as:

\[ H_{\text{ui}}(p) = K_{\text{ui}} \prod_{i=1}^{N} \left( \frac{1+\alpha_i p}{p^2 + 2\xi_i p + \omega_i^2} \right) \exp(-\tau_{\Sigma} p) \]

Here: \(0 \leq \xi_i < 1\) - i-zone empirical dissipative coefficient; \(\alpha_i p\) - forcing term; \(\tau_{\Sigma}\) - summary transport delay.

We can count function's parameters by the least square algorithm for AR-model. The final example concerns the transfer function of admittance for SPT-76 near the nominal working point (discharge voltage \(U_{do}=200\) V, mass flow rate \(Xe M_{o}=2.2\) mg/sec, discharge current \(I_{do}=2.31\) A, magnetic system current \(I_s = 2\) A). The approximate function orders was selected to be \(N\) and \(\overline{N}\):

\[ H_{\text{ui}} = K_{\text{ui}} \prod_{i=1}^{\overline{N}} \left( \frac{1+\alpha_i p}{p^2 + 2\xi_i p + \omega_i^2} \right) \exp(-\tau_{\Sigma} p) \]

Mode optimization of both power system and EP-system by the control system.

In the case of PPS power capability varying the mode optimization criterion can be got as:

\[ J = g_1 [\zeta(t)-\zeta_0]^2 + g_2 [F(t)-F_0]^2 \rightarrow \text{MIN} \]

(2)

here \(\zeta(t)\) and \(\zeta_0\) are varying and nominal specific impulses, respectively; \(F(t), F_0\) are varying and nominal thrust levels; \(g_1, g_2\) are weight coefficients.

The present control method is the change over of SPT to quasi-stationary mode for the purpose to throttle deeply the power level of SPT in accordance with PPS power capabilities.

Owing to great problems to measure the thrust level on the spacecraft board the Taylor decomposition could be acceptable to the thrust estimation as:

\[ F(t) = F_0 + K_F (U_d(t) - U_{do}) + K_m (\dot{\epsilon}(t) - \dot{\epsilon}_0) + \Delta F(\delta I_s) \]

(3)

here: \(U_d(t)\) is effective discharge voltage (including the pulse mode); \(\dot{\epsilon}(t)\) is mass flow rate of a gas propellant; \(U_{do}\) and \(\dot{\epsilon}_0\) are nominal value of the discharge voltage and the mass flow rate; \(K_F, K_m\) are decomposition coefficients.

Because of difficulties to regulate parameters of SPT by the level of the magnetic field (by the solenoid current - \(I_s\)) the function converter of the control system can generate \(\Delta F\) levels proportional to \(U_d(t)\) robustly with optimal discharge current \(I_d\) fixing. Now, there are only two control inputs \(U_d, \dot{\epsilon}\) for SPT thrust regulation.

The PLM mode optimization of SPT can be selected for PPS power decreasing. The input signal for PLM control system can be defined from the PPS voltage drop \(\Delta u\) preferably.

Hence, the function of the pulse width variation can be defined as:

\[ \Delta t(t) = \frac{1}{fi - ku \Delta u(t)} \]

and PLM effective voltage can be written as:

\[ U_d(t) = \Phi u_{do} - ku \Delta u \]
where $\phi$ is the pulse shape coefficient.

The control connection $K_{mF}(U_d-U_{do})=-(\dot{\lambda}-\lambda)$ minimizes criterion (3) and reduces to single input regulation with extreme condition:

$$\phi(t)=-\Delta -\lambda$$

EP-system control subsystem is shown in Fig. 4 and consists of thermostrottle flow controller, feedback control subsystem of the magnetic system current, discharge circuit equipped with PLM modulator and voltage/current sensors. The function converter forms discharge current levels as mentioned.

Generally, the system compensates quickly the variations of PPS voltage as well as PF voltage drops by means of the discharge voltage modulation. After that the system slowly changes the flow rate level directing SPT to new stationary operation point. In case when the range of flow controller was limited (thermostrottle heat is highest) SPT is remained quasi-state mode during power decrease.

The EP control subsystem operating with SPT-76 is illustrated in Fig. 5 by simulation.

Conclusions

The operation optimizing of EP-system with deep throttling (control) subsystem may be applied to high power SPT as well as small SPT for conditions of limited power capabilities.

References


Fig. 1. Pulse frequency vs. thrust level, gram
- x - 40 kHz
- - 7 kHz
- - 60 kHz
- - 20 kHz

Fig. 2. Thrust level, gram
Ud = 150 V or 300 V
Ud = 0.5 V

Fig. 3. Discharge current, Amp
Frequency, kHz
Time, microseconds

Quasi-stationary mode responses of SPT-70
Fig. 4. SPT control subsystem

Fig. 5. Time responses of EP-system equipped with control subsystem