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DESIGN OF A MULTIFUNCTIONAL ELECTRIC PROPULSION SUBSYSTEM OF THE SPACECRAFT

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A common way to form an electric propulsion subsystem of the spacecraft is to create specialized equipment or to select the most suitable one from the ready-made ones. However, there are cases when the use of existing equipment is not optimal enough and leads to an unjustified increase of the subsystem mass. Therefore, the question of creating a minimum equipment set possibility from which it would be possible to form propulsion subsystems in optimal way is of interest. The set of tasks, variants of use and possible schemes of placing orbital correcting propulsion on the spacecraft are presented. The list of necessary propulsion subsystem elements is presented as follows: a thruster block, a tank, a xenon feed unit, a power processing unit consisting of a power unit and switching units, the complete set of cables and pipelines, the software and mechanical devices for control of the thrust vector (as an option). The necessary capacity of propellant tanks for the tasks of correction and raising of the satellite to GEO with a high-pulse Hall thruster is defined: for orbit correction tasks – up to100 kg, for orbit correction and raising to GEO tasks – up to200 kg. Necessary angle rates of mechanical devices for control of the thrust vector are defined taking into account possible schemes of placing thrusters on the spacecraft. It is shown that in cases when it is required to apply two or more thrusters to increase overall thrust, it is more preferable in the weight aspect to apply a combination of power and switching units instead of monoblock type of power processing units, and advantage can reach tens of kilograms. Provided the listed set of functional units is created, the offered concept will make it easy to form propulsion subsystems of the spacecraft for solving a wide range of tasks. It will reduce the time and money spent on creation of propulsion subsystem for new spacecrafts.

Keywords: thruster, spacecraft, power processing unit, tank, propellant feed unit, orbit correction.

ПОСТРОЕНИЕ МНОГОФУНКЦИОНАЛЬНОЙ ЭЛЕКТРОРЕАКТИВНОЙ ДВИГАТЕЛЬНОЙ ПОДСИСТЕМЫ КОСМИЧЕСКОГО АППАРАТА

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Распространенным способом формирования электрореактивной двигательной подсистемы космического аппарата является создание специализированного оборудования или подбор наиболее подходящего из уже готового. Однако нередки случаи, когда применение имеющегося оборудования недостаточно оптимально и приводит к неоправданному увеличению массы подсистемы. Поэтому представляет интерес вопрос о возможности создания некоторого минимального набора оборудования, из которого можно было бы оптимальным образом формировать двигательные подсистемы. Представлен набор задач, варианты использования и возможные схемы размещения двигателей коррекции орбиты на космическом аппарате. Перечень необходимых элементов электрореактивной двигательной подсистемы представлен следующим образом: блок коррекции, бак, блок подачи рабочего тела, система преобразования и управления, состоящая из отдельно выполненного силового блока и коммутационных блоков, комплект кабелей и трубопроводов, программное обеспечение *и приводные механизмы для управления вектором тяги двигателей (как опция). Определена необходимая вместимость баков рабочего тела для задачи коррекции и довыведения спутника на геостационарную орбиту при использовании высокоимпульсного холловского двигателя: до 100 кг для задач коррекции орбиты, до 200 кг для задач довыведения и коррекции. С учетом схемы размещения двигателей на корпусе космического аппарата определены требуемые углы прокачки для механизмов управления вектором тяги двигателей. Показано, что в случаях, когда для увеличения суммарной тяги требуется применять два и более двигателя, в весовом отношении выгоднее применять вместо моноблочных систем преобразования и управления комбинацию из силовых и коммутационных блоков, причем преимущество может достигать десятков килограммов. При условии создания перечисленного набора функциональных блоков предложенная концепция позволит легко формировать двигательные подсистемы космических аппаратов для решения достаточно широкого круга задач. Это позволит снизить затраты времени и средств на создание двигательных подсистем для новых космических аппаратов.*

Ключевые слова: двигатель, космический аппарат, система преобразования и управления, бак, блок подачи рабочего тела, коррекция орбиты.

Inroduction. A considerable part of automatic spacecraft (SC) contains propulsion subsystems that perform the tasks of correcting the orbit and controlling the angular position of the spacecraft. These subsystems can be built on the basis of chemical fuel thrusters or on the basis of electric propulsion (EP). Of the many types of EP, the most widespread are ion and plasma thrusters [1]. They are mainly used for tasks requiring high total pulse costs (from 3000 kNs and more). Their advantage over thrusters using chemical fuels lies in significantly greater propellant savings. However, to use EP it is necessary to apply special on-board electronic devices (in the domestic literature – conversion and control systems (SPU), in the foreign literature – Power Processing Unit (PPU)), which convert the on-board supply voltage to the voltage necessary for the thruster to work.

The choice of thruster size and the construction of the propulsion subsystem including the PPU architecture, depends on the size and type of the spacecraft and the amount of tasks assigned to the propulsion subsystem. This volume, characterized by the magnitude of the total momentum and thrust, can vary by several times. Accordingly, the concept of the propulsion subsystem that solves these problems should be significantly different. Obviously, the best solution in terms of minimum total mass is to build a propulsion subsystem based on specially designed blocks for each individual task. However, the creation of new blocks of the subsystem (thrusters, tanks, PPU) is associated with significant cost and time. Therefore, in practice, a different approach is often used - the formation of the propulsion subsystem based on a ready-made one, that is experimentally tested or flight-qualified units. This raises the question of what should be the set and concept of these blocks, from which it would be possible to build the propulsion subsystems of different SC, easily adapting to various tasks. This article is devoted to consideration of this issue. The concept of building a multifunctional electric propulsion subsystem based on a limited number of types of constituent elements is presented.

The list of tasks for the multifunctional electric propulsion subsystem. The following tasks for the multifunctional propulsion subsystem used on automatic SC can be formulated:

1) correction of the orbit of the geostationary SC;

2) raising a spacecraft to GSO and correcting its orbit;

3) raising a spacecraft to GSO and correcting its orbit with the simultaneous creation of control moments;

4) correction of the spacecraft orbit in the HEO (highly elliptical orbit);

5) finding main stage solutions for placing the interorbital transfer of payloads or the scientific spacecraft to the bodies of the solar system, service unmanned spacecraft flight support (servicing the spacecraft in the GSO, towing spent satellites into disposal orbit, etc.);

The composition of the multifunctional propulsion subsystem and the architecture of power processing units can be different depending on the tasks to be solved and the selected configuration of thrusters. These differences are a consequence of optimization of the propulsion subsystem in terms of mass characteristics.

The composition of the electric propulsion subsystem. According to the tasks, the full composition of the electric propulsion subsystem can be determined in the following way.

1) A propulsion unit or a correction unit, consisting, as a rule, of a gas distribution unit (BGR) and a thruster itself, containing an anode block and two cathodes. Note that the domestic school traditionally prefers the use of two cathodes in order to reserve this rather complex and loaded element, but in foreign practice, cathode reservation has not been used recently, based on operating experience and calculated cathode reliability indicators.

The number of propulsion units in the system can be different depending on the tasks being solved – from 1 to 8.

Both an ion and a plasma thruster can be used as an thruster for a multifunctional electric propulsion subsystem. In this article, we consider the use of a high-pulse plasma thruster, for example, from a number of thrusters developed at the Keldysh Center [2] or at the Fakel Design Bureau [3]. This type of thruster has a number of advantages over an ionic one: smaller mass and dimensions, relative cheapness with comparable efficient performance.

2) Power Processing Unit (PPU). It is necessary to power one, two, three or four thruster units as selected from a specific set. Various possible approaches will be discussed below. The importance of the search for optimal solutions for the construction of the PPU is due to the following factors specific to this device:

– significant mass;

– a large number of electronic elements, high complexity of the device as a whole;

– the high cost of flight samples;

– significant cost and time when developing new designs.

3) The propellant tank (xenon storage unit). The mass of the propellant tank is important due to large refueling. When designing a subsystem, various approaches are possible: an individual tank for each required refueling or a set of standard tanks of relatively small dimension or one large tank that allows various refuels. Obviously, the chosen concept should provide the minimum mass of the tank design or set of tanks for each typical task or groups of tasks with similar requirements.

4) Xenon feed unit. This device is necessary to lower the inlet (tank) pressure to the pressure required by the operating conditions of the thruster. The range of gas flow rates provided by such a device can be very large – from milligrams (for powering the plasma thruster) to grams per second (for powering gas-jet nozzles, if a gas-reactive system is used instead of a separate mono-fuel attitude propulsion subsystem).

5) A set of pipelines and cables connecting gas and electricity sources with recipients.

6) On-board software (OBSW) for controlling the subsystem blocks.

7) Mechanical drives for controlling the thrust vector of thrusters (as an additional option). If such devices are available, it is necessary to provide an auxiliary gas-reactive system to create control moments in the initial modes and modes of ensuring the survivability of the spacecraft.

The number of thrusters can be different depending on the tasks to be solved. This issue should be considered in more detail, since the thrusters and their number are determining factors in specifying the appearance of the propulsion subsystem. So, for task 1 (correction of the geostationary spacecraft orbit) with rigid fixing of the thrusters, the number of thrusters can vary from 4 to 8 (for example, 4, 6, 8). There are examples of spacecraft with 8 thrusters (4 for longitude correction, 4 for inclination correction, fig. 1) with cold reserve, that is, 4 thrusters are the main, 4 are the reserve. There are examples of applying the scheme with a reduced number of thrusters: 6 (2 for longitude correction, 4 for inclination correction, fig. 2) or 4 universal thrusters used both for longitude correction and inclination correction with functional redundancy (fig. 3).

Correcting the orbit of a geostationary spacecraft with a mass of 3–4 tons, thrust up to 80–100 mN is sufficient, which can be provided by one thruster [4]. Therefore, to solve the above problems, one redundant power supply and control device with the ability to power one thruster out of 8 or one of 4 is enough. A variant with 6 thrusters can be provided with some redundancy by a PPU with powering one thruster out of 8.

For task 2 (raising a spacecraft to GSO and correcting its orbit), it is necessary to provide increased thrust at the raising stage to reduce the time of raising. For this purpose special thrusters of increased thrust and power (for example, type SPD-140) can be used. However, from a structural and operational point of view, it is more convenient to use thrusters of the same type on board, and to increase thrust at the raising stage make thrusters run together or in a large number, if the available power of the power supply system (PSS) of the spacecraft allows.

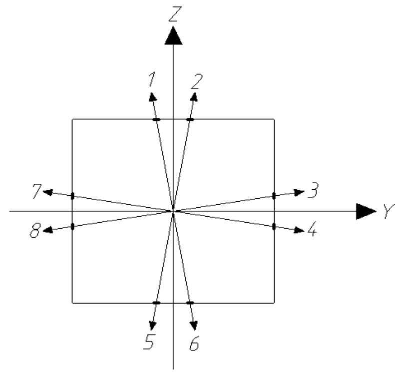

Fig. 1. Eight orbit correction thrusters placing in ±Y, ±Z directions (4 main, 4 reserve)

Рис. 1. Размещение 8 двигателей коррекции для коррекции орбиты в направлениях ±Y, ±Z (4 основных, 4 резервных)

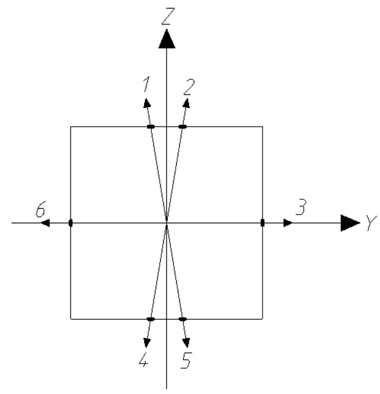

Fig. 2. Six orbit correction thrusters placing in ±Y, ±Z directions

Рис. 2. Размещение 6 двигателей коррекции для коррекции орбиты в направлениях ±Y, ±Z

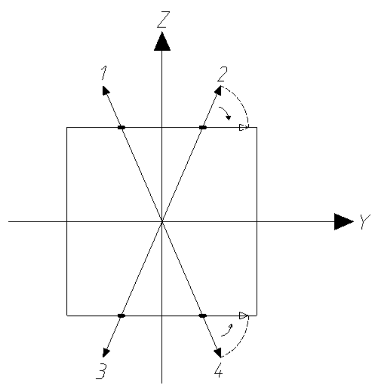

Fig. 3. Four orbit correction thrusters placing in ±Y, ±Z directions. Functional reserve

Рис. 3. Размещение 4 двигателей коррекции для коррекции орбиты в направлениях ±Y, ±Z. Резервирование – функциональное

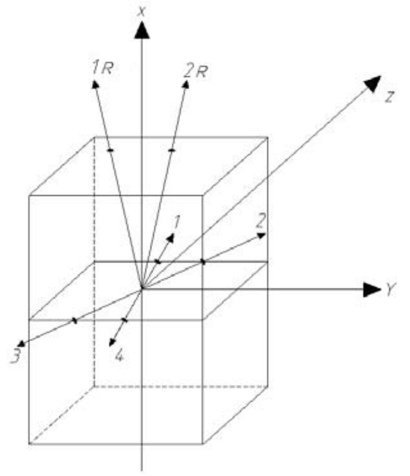

Fig. 4. Four orbit correction thrusters placing
and two orbit raising thrusters (R) placing

Рис. 4. Размещение четырех двигателей
коррекции для коррекции орбиты
и двух двигателей для довыведения

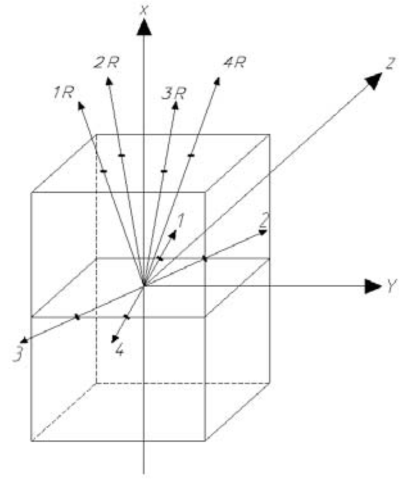

Fig. 5. Four orbit correction thrusters placing
and four orbit raising thrusters (R) placing

Рис. 5. Размещение четырех двигателей
коррекции для коррекции орбиты
и четырех двигателей для довыведения

When there is a rigid fixing on the body of the spacecraft, it is advisable to use at least 2 separate thrusters at the same time; that is, the usual scheme of 4 or 6 correction thrusters should be supplemented with two more extension thrusters (fig. 4). It is advisable to place them along the + X axis, directing a jet stream into an area free of spacecraft structural elements. For the thrust impulse to be produced by these thrusters in the ± Y direction, that is, along the velocity vector, the satellite must be turned around the Z axis by 90°. It is also necessary to provide the ability to power 2 thrusters at the same time from a choice of 6 or 8. It should be noted that at the raising stage due to its limited time (no more than six months with a service life of 15 years or more), it is possible to do without reservation of power converters in the PPU, and use 2 thrusters.

If the thrust of 2 thrusters at the raising stage is not enough, then one or two thrusters can be additionally used (within the available power of the PSS), (fig. 5). It means that facilities should be provided to power them.

When installing thrusters on drives similar to European ones developed for the EUROSTAR 3000 spacecraft [5] for example, there is a possibility in principle to obtain the thrust of two thrusters at the same time in the same direction in addition to creating control moments along at least two axes (see. fig. 3). In this case, it is necessary to power two thrusters out of 4.

Construction of a power processing unit of thrusters. An important issue is the formation of the construction concept of the PPU to provide power to the thrusters. The traditional approach is to create a specialized device for the most common applications of thrusters, that is, to ensure the operation of one thruster from as selected 2, 4 or 8 [6; 7].

However, to solve the whole spectrum of problems, especially where simultaneous operation of two or more thrusters is required, the use of such control systems is not rational enough, since it requires the use of two or more control systems, or the development of special modifications of the device for simultaneously powering several thrusters, which is irrational, as it leads either to additional mass costs, or requires a new development with the corresponding costs of time and money. It is possible to propose another approach, which will minimize both the mass costs for solving various problems, and the costs of developing PPU. According to this concept, it is necessary to separate the tasks, that is, to create an unreserved power block that allows directly (without switching) powering one thruster and two switching blocks - to power one of two thrusters (we will designate it conventionally SU-2) and one thruster of four (SU-4). It is shown below, in tab. 1 and fig. 6–14 that a combination of these three blocks can provide, with the necessary level of redundancy, the supply of one, two, three, four thrusters from a certain set. Possible options for powering the PU using power and switching units are presented graphically in fig. 6–14.

Evaluations based on the current level of commutation technology excellence show that when solving tasks involving only one thruster during the entire mission (powering one of four, six, or eight thrusters), the option of using monoblock PPUs is more preferable. However, if it is necessary to power two or more thrusters, the use of the above mentioned combination of power and switching units can achieve significant mass savings while maintaining the required level of redundancy. Moreover, the advantage can reach tens of kilograms, which is a very significant amount, which may justify the costs of the development of power and switching units.

For the case when simultaneous operation of two thrusters at the same time for a limited period of time is required (for example, when raising a spacecraft to GSO), the cold reserve in the power unit can be abandoned, and then only two power units are used, in this case the weight advantage of the options based on combinations of power and switching units is increasing even more.

Table 1

Options for constructing a thruster power circuit

Task	Number of thrusters	Powering option	Number of units					ΔM_{Σ} [kg]***
			Monoblock PPU version		Version based on a power unit and switching units			
			PPU for powering 1 out of 4 thrusters	PPU for powering 1 out of 8 thrusters	Power unit	SU-2	SU-4	
Geostationary and highly elliptical SC								
1. Correction of GSO	8	1 out of 8	–	1	2	–	2*	Minus 13
2. Correction of GSO	6	1 out of 6	–	1	2	1*	1*	Minus 8
3. Correction of GSO	4	1 out of 4	1	–	2	–	1	Minus 8
4. Correction of HEO	4	2 out of 4 constant	2	–	3**	–	1*	11
5. Correction of HEO	6	2 out of 6 constant	–	2	3**	1*	1*	18.5
6. Final ascent and correction of GSO	4	2 out of 4 temporary, 1 out of 4 constant	2	–	2	–	1	25.5
7. Final ascent and correction of GSO	6	2 out of 6 temporary, 1 out of 6 constant	0	2	2	1*	1*	33
8. Final ascent and correction of GSO	8	2 out of 8 temporarily, 1 out of 8 constant	0	2	2	–	2*	28
9. Accelerated final ascent and correction of GSO	8	4 out of 8 temporary, 1 out of 4 constant	4	–	4	1*	1*	56
Sustainer task								
10. Long continuous operation (acceleration, braking)	2	2 out of 2	2	–	3**	1	–	16
					2	–	–	38
11. Long continuous operation (acceleration, braking)	3	3 out of 3	3	–	4**	–	1	30
					3	–	–	57
12. Long continuous operation (acceleration, braking)	4	4 out of 4	4	–	5**	–	1	49
					4	–	–	76

* if using splitter cables;
** one power unit in cold reserve;
*** the difference in the total mass of the monoblock PPU version and the variant based on the power unit and switching units.

Thus, the concept of dividing the PPU into power and switching units is more flexible and allows solving various problems that require the operation of several thrusters in a more optimal way compared to the option of monoblock PPU. There are also options with direct power supply of thrusters without switching blocks. In this case, each thruster has its own power unit. The number of such sets of thruster-PPU can be from one to four in a reasonable range of available power of the PSS. Another important advantage of the concept of constructing a conversion and control system on the basis of individual blocks is the absence of the need to develop new variants of monoblock PPU for each new task, which makes it possible to significantly reduce the time and money spent on creating a propulsion subsystem.

Estimation of required tank capacity. For the typical task of raising and correcting the orbit of a geostationary spacecraft with a mass of 3000 kg for a service life of 15 years, about 4100 kNs (≈420 t·s) of the total pulse is required. It is advisable to choose a thruster with a power of about 2 kW with a specific impulse of up to 2700 s as a thruster for a promising propulsion subsystem. With this specific impulse, 156 kg of xenon will be required to produce this total impulse.

Taking into account 10 % of the reserve for leaks, non-produced balance and guarantee stock, refueling should be 170 kg.

Taking into account an additional 10–15 kg to ensure the operation of the pneumatic system on cold gas, which is necessary for passing the initial orientation modes and survivability modes in the version of the system with drives, the total stock will be up to 187 kg. Thus, a tank capacity of 200 kg of xenon is sufficient to ensure the listed tasks.

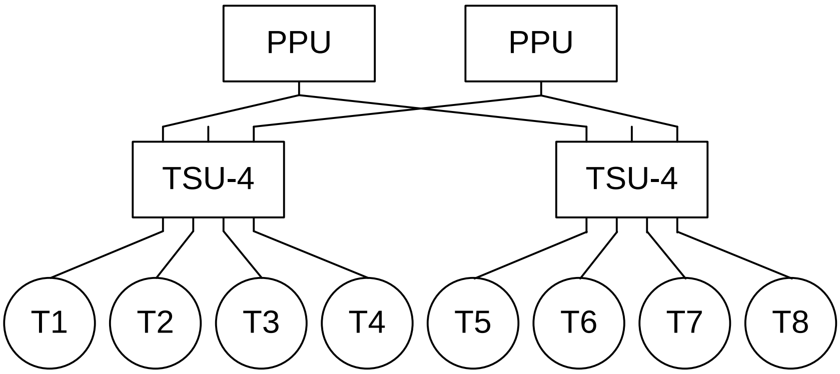

Fig. 6. The powering of one out of eight thrusters or temporary powering
of two out of eight thrusters and constant powering of one out of eight thrusters

Рис. 6. Запитка одного двигателя из восьми или двух из восьми временно
и одного из восьми постоянно

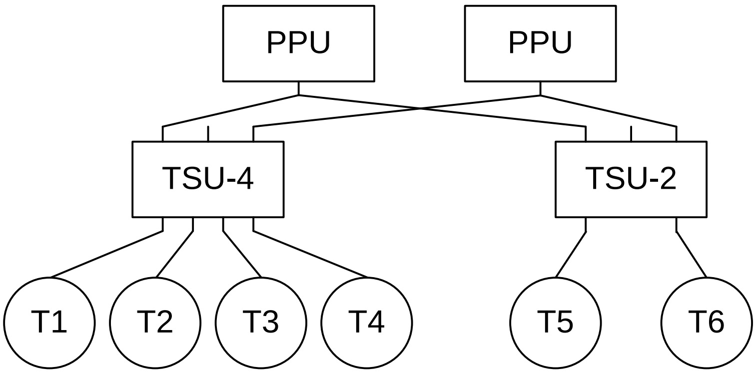

Fig. 7. The powering of one out of six thrusters or temporary powering
of two out of six thrusters and constant powering of one out of six thrusters

Рис. 7. Запитка одного двигателя из шести или двух из шести временно
и одного из шести постоянно

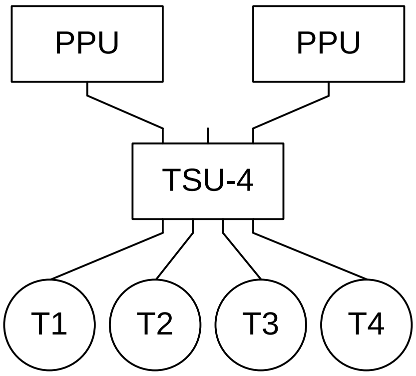

Fig. 8. The powering of one out of four thruster or temporary powering
of two out of four thrusters and constant powering of one out of four thrusters

Рис. 8. Запитка одного двигателя из четырех или двух из четырех временно
и одного из четырех постоянно

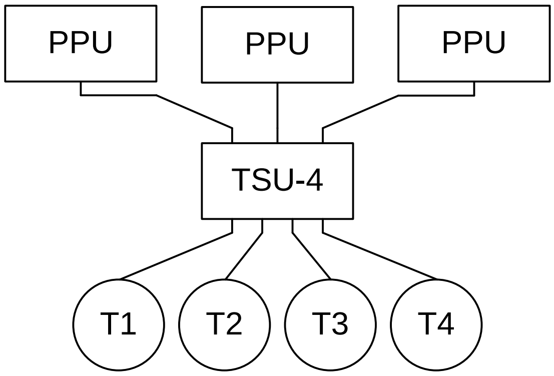

Fig. 9. Constant powering of two out of four thrusters

Рис. 9. Запитка двух из четырех двигателей постоянно

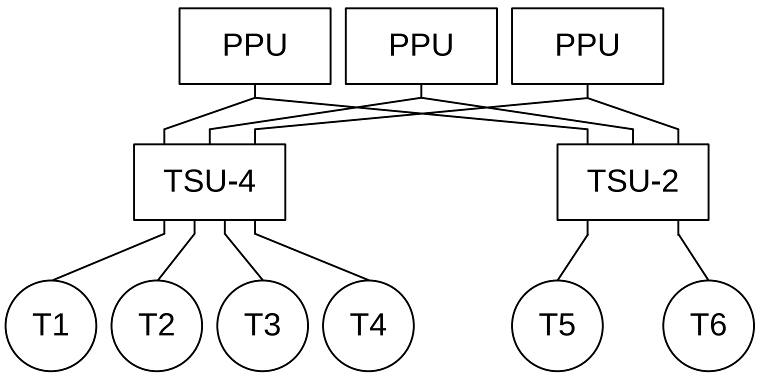

Fig. 10. Constant powering of two out of six thrusters

Рис. 10. Запитка двух из шести двигателей постоянно

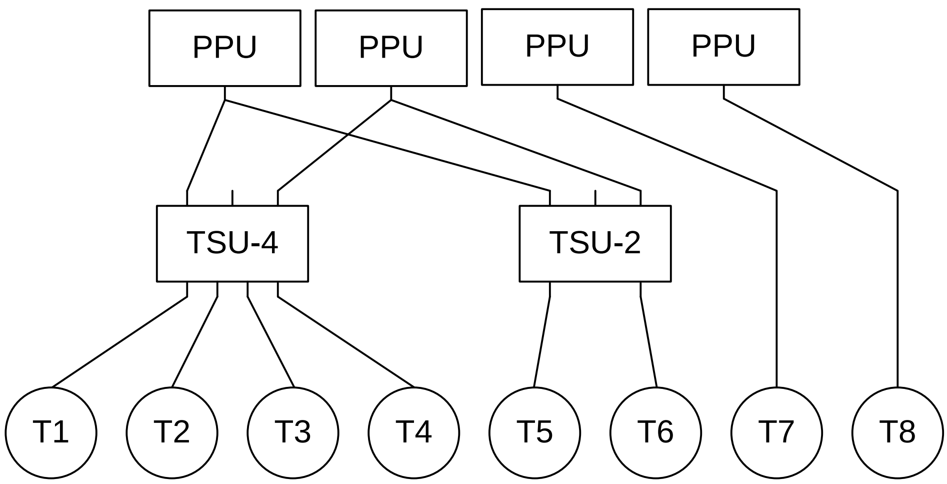

Fig. 11. Temporary powering of four out of eight thrusters and constant powering of one out of four thrusters

Рис. 11. Запитка четырех из восьми двигателей временно и одного из четырех постоянно

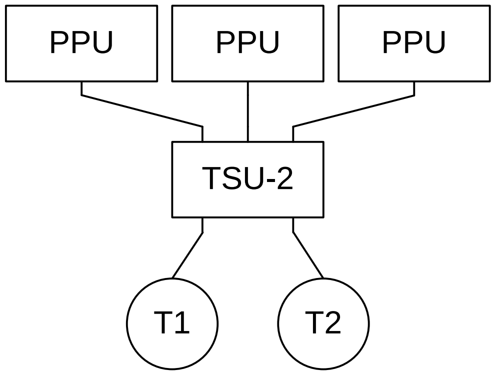

Fig. 12. Constant powering of two out of two thrusters with PPU reservation

Рис. 12. Запитка двух из двух двигателей постоянно с резервированием по силовому блоку

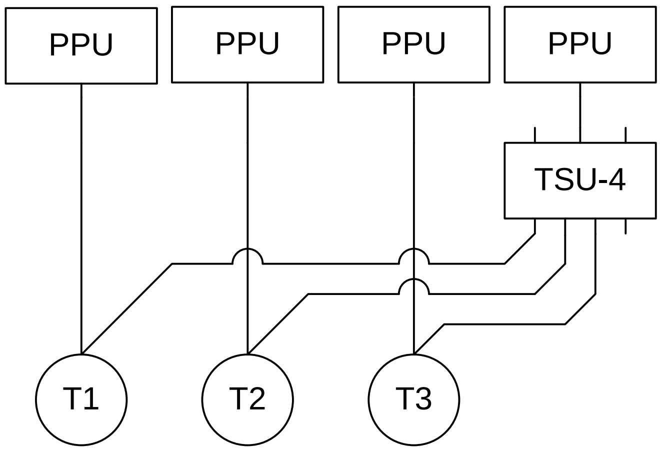

Fig. 13. Constant powering of three out of three thrusters with PPU reservation

Рис. 13. Запитка трех из трех двигателей постоянно с резервированием по силовому блоку

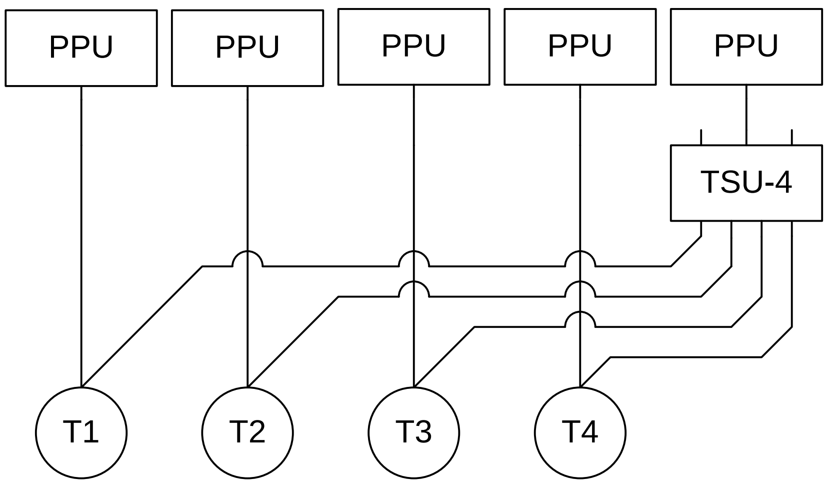

Fig. 14. Constant powering of four out of four thrusters with PPU reservation

Рис. 14. Запитка четырех из четырех двигателей постоянно с резервированием по силовому блоку

Table 2

The quantitative composition of the constituent elements of the propulsion subsystem for the solution of various tasks

Unit	Possible number in the propulsion subsystem
PU (thruster)	up to 8
PPU (power unit)	up to 5
SU-2 (switching unit with output to 2 thrusters)	up to 2
SU-4 (switching unit with output to 4 thrusters)	up to 2
XFU (high flow rate xenon feed unit)	1
T-100 (100 kg tank)	1
T-200 (200 kg tank)	1
Cable set	1
Pipeline set	1
On-board software (OBSW), set	1
Gas-jet nozzles (for version with actuators)	up to 8
Additionally	
Two-stage drive with flow angles ± 90°	4
Orientation device with two-stage drives and rods	2

It should be noted that in the presence of a monofuel propulsion subsystem, it is possible to abandon a pneumatic system using cold gas and drives to create control moments.

If the task of final ascent is not set, then about 200 t·s from the total impulse will be enough to ensure orbit correction. Consequently, a tank capacity of 100 kg is sufficient, taking into account the reserve for leaks, non-produced balance, guarantee balance and reserve to ensure the operation of the pneumatic system on cold gas (if any). Thus, for the operation of the propulsion subsystem, it is enough to have tanks with a capacity of 100 and 200 kg. It is desirable that the tanks have identical dimensions and design, different only in the thickness of the pressure restraint layer and weight, for example, on the basis of the tank developed at ISS JSC [8]. If it is necessary the combination of such tanks can easily obtain a total capacity of 300 and 400 kg. Taking into account the actually achieved perfection of the design of the tanks, characterized by the value of the tank coefficient (the ratio of the mass of the tank to the maximum refueling) of about 0.1, the mass savings in the case of creating a tank with a capacity of 200 kg can reach about 10 kg, for a tank with a capacity of 100 kg – up to 20 kg compared to the option of placing the stock of the propellant in a tank with a capacity of 300 kg.

Xenon feed unit requirements. When xenon consumption in one thruster is about 4 mg/s and there is a simultaneous operation of up to 4 thrusters, then it is necessary to ensure consumption up to 16 mg/s. When maximum 4 nozzles operate simultaneously it is necessary to ensure a flow rate of about 1.6 g/s for the pneumatic system to work on cold gas. Thus, when there is a pneumatic system, a xenon feed unit with a very large flow range from 4 mg/s to 1.6 g/s is needed.

Basic requirements for the drive (orientation mechanism) of thrusters. a cross-shaped arrangement of 4 thrusters (fig. 3) is taken as a basis with an optimal deviation of the thrust line from the Z direction of 20–25 °, then to create thrust in the Y direction (for a final ascent) it is necessary to deploy two thrusters at an angle of about 70°. To provide pitch control torque (around the Z axis), one or two thrusters must be turned towards ± X at an angle of about 90°. Thus, it is desirable to have a two-stage drive for one thruster with pumping angles up to ± 90°. If rods are also provided for changing the position of the thrusters, drives of this type can be placed in their root and end parts.

In view of the foregoing, the quantitative composition of the constituent elements of the propulsion subsystem for the solution of the tasks enumerated in tab. 1 is presented in tab. 2.

Conclusion. It is shown that if a high-pulse plasma thruster with a power of 2 kW, a power converter unit, switching units with access to two and four thrusters, a xenon feed unit with a wide flow range, tanks for 100 and 200 kg of xenon, and also, as an additional options, two-stage drives or combinations of drives with rods are created, then it is possible to form an electric propulsion subsystem for solving a wide range of tasks – from orbital correction in the simplest version of four motionless mounted thrusters to a multifunctional system that provides raising a spacecraft to the GSO, orbit correction and creation of control moments. The presence of these blocks will also allow the formation of propulsion subsystems for solving various sustainer tasks in a fairly wide range of available power of the onboard power supply system. The construction of a conversion and control system in the form of separate power and switching units will allow in many cases to reduce weight, simplify the formation of the propulsion subsystem as a whole, and reduce the cost of its development. Thus, if the presented concept is implemented, it will create conditions for expanding, in justified cases, the scope of application of electric propulsion subsystems and increasing on this basis the overall efficiency of a spacecraft by reducing the mass of the propulsion subsystem compared to alternative types, in particular subsystems based on chemical thrusters.

References

1. Lev D., Myers R. V., Lemmer K. M. et al. The Technological and Commercial Expansion of Electric

Propulsion in the Past 24 Years. *35th Electric Propulsion Conference*. IEPC-2017-242. Georgia Institute of Technology. USA, October 8–12, 2017, 18 p.

2. Lovtsov A. S., Tomilin D. A., Muravlev V. A. Development of the high-voltage Hall-effect thrusters in the Keldish Research Centre. *68th International Astronautical Congress*. IAC-17-C4.4.4, Adelaide, Australia, 25–29 September 2017, 5 p.

3. Gnizdor R., Komarov A., Mitrofanova O., Saevets P., Semenenko D. High-impulse SPT-100D Thruster with discharge power of 1.0…3.0 kW. *The 35th International Electric Propulsion Conference, Georgia Institute of Technology*. USA, October 8–12, 2017, 8 p.

4. Ermoshkin Yu. M., Bulynin Yu. L. [Assessment of the minimum permissible thrust of engines for correcting the orbit of geostationary satellites]. *Upravlenie dvizheniem i navigaciya letatelnykh apparatov. Chast 1. Sbornik trudov XIII Vserossiiskogo nauchno-tekhnicheskogo seminara po upravleniyu dvizheniem i navigacii letatelnykh apparatov*. Samara, 13–15 june 2007. P. 109–111 (In Russ.).

5. Falkner M., Nitschko T., Zemann J., Mitterbauer G., Traxler G. Electric Propulsion Thruster Pointing Mechanism (TPM) For EUROSTAR 3000: Design & Development Test Results. *The 29th International Electric Propulsion Conference*. IEPC-2005-001. Princeton University, Okt. 31 – Nov. 4, 2005, 10 p.

6. Gollor M., Schwab U., Boss M., Bourguignon E. et al. Power Processing Units – activities in Europe 2015. *34th International Electric Propulsion Conference*. IEPC-2015-225, Kobe-Hyogo, Japan, July 4–10, 2015, 13 p.

7. Gladuchenko V. N., Galaiko V. N., Gordeev K. G., Ermoshkin Yu. M., Mikhailov M. V., Yakimov E. N. Modern status and future directions of evolution of power processing units for electric plasma thrusters. *Electronic and electromechanical systems and devices*. Scientific papers, JSC “NPC “Polus”. Tomsk Polytechnic University Press, 2016, p. 59–65.

8. Kravchenko I. A., Mikheev A. V., Borodin L. M. Application features of metal composite tanks on board of SC. *Proceedings of XYII International conference “Reshetnevskie chteniya”*. 12–14 November, Krasnoyarsk, 2013, P. 71–72.

9. Ermoshkin Yu. M., Yakimov E. N On the concepts of the station keeping and geostationary orbit injection thruster’s application. *Proceedings of XVI International conf. “Aviation and Space”*. Moscow, 2017, Nov. 20–24, P. 92–93.

10. Ermoshkin Yu. M. [Electric propulsion’s rational application range on the applied spacecrafts]. *Vestnik SibGAU*. 2011, No. 2 (35), P. 109–113 (In Russ.).

11. Yermoshkin Yu. M., Volkov D. V., Yakimov E. N. On the concept of “all electric propulsion spacecraft”. *Siberian Journal of Science and Technology*. 2018, Vol. 19, No. 3, P. 489–496. Doi: 10.31772/2587-6066-2018-19-3-489-496.

12. Ostrovsky V. G., Sukhov Yu. I. [Development and operation of electric thrusters and electric propulsion systems at OKB-1 – TsKBEM – NPO “Energia” – RSC “Energia” named S.P.Korolev (1958-2011)]. *Raketno-kosmicheskaya tekhnika. Trudy*. 2011. Ser. XII., Iss. 3–4, P. 122–127 (in Russ.).

13. Khodnenko V. P. Activities of VNIIEM in EPT field. History, our days and prospects. *33rd International Electric Propulsion Conference*. IEPC-2013-65. The George Washington University. D.C. US. October 6–10, 2013.

14. De Tata M., Frigor P., Beekmans S. et al. SGEO Electric Propulsion Subsystem Development Status and Future Opportunities. *33rd International Electric Propulsion Conference*. IEPC-2013-144. The George Washington University, USA, October, 6–10, 2013, 11 p.

15. Ferreira J. L., Martins A. A., Miranda R. A. et al. Development of a Solar Electric Propulsion System for the First Brazilian Deep Space Mission. *35th Electric Propulsion Conference*. IEPC-2017-166. Georgia Institute of Technology. USA, October 8–12, 2017, 14 p.

Библиографические ссылки

1. The Technological and Commercial Expansion of Electric Propulsion in the Past 24 Years / D. Lev, R. V. Myers, K. M. Lemmer et al. // 35th Electric Propulsion Conference. IEPC-2017-242. Georgia Institute of Technology. USA, October 8–12, 2017. 18 p.

2. Ловцов А. С., Томилин Д. А., Муравлев В. А. Разработка высоковольтных холловских двигателей в Центре Келдыша // 68th International Astronautical Congress. IAC-17-C4.4.4, Adelaide, Australia, 25–29 September 2017. 5 p.

3. High-impulse SPT-100D Thruster with discharge power of 1.0…3.0 kW / R. Gnizdor, A. Komarov, O. Mitrofanova et al. // The 35th International Electric Propulsion Conference, Georgia Institute of Technology. USA, October 8–12, 2017. 8 p.

4. Ермошкин Ю. М., Булынин Ю. Л. Оценка минимально допустимой тяги двигателей коррекции орбиты геостационарных спутников // Управление движением и навигация летательных аппаратов : сб. тр. XIII Всеросс. науч.-технич. семинара по управлению движением и навигации летательных аппаратов / Самар. гос. аэрокосмич. ун-т им. акад. С. П. Королева. Самара, 13–15 июня 2007 г. Ч. I. С. 109–111.

5. Electric Propulsion Thruster Pointing Mechanism (TPM) For EUROSTAR 3000: Design & Development Test Results / M. Falkner, T. Nitschko, J. Zemann et al. // The 29th International Electric Propulsion Conference. IEPC-2005-001. Princeton University, Okt. 31-Nov. 4, 2005. 10 p.

6. Power Processing Units – activities in Europe 2015 / M. Gollor, U. Schwab, M. Boss et al. // 34th International Electric Propulsion Conference. IEPC-2015-225, Kobe-Hyogo, Japan, July 4–10, 2015. 13 p.

7. Современное состояние и перспективы развития систем преобразования и управления электрореактивными плазменными двигателями / В. Н. Гладущенко, В. Н. Галайко, К. Г. Гордеев и др. // Электронные и электромеханические системы и устройства : сб. науч. тр. Томск : АО НПЦ «Полюс» ; Изд. Томского политехнич. ун-та. 2016. С. 59–65.

8. Кравченко И. А., Михеев А. В., Бородин Л. М. Особенности применения металлокомпозитных баков на борту КА // Решетневские чтения : материалы XVII междунар. науч.-технич. конф. Красноярск, 12–14 ноября 2013. Ч. 1. С. 71–72.

9. Ермошкин Ю. М., Якимов Е. Н. О концепциях применения двигателей коррекции и довыведения // Авиация и космонавтика – 2017 : тез. доклада 16-й Междунар. конф. Москва, МАИ, 20–24 ноября 2017. С. 92–93.

10. Ермошкин Ю. М. Области рационального применения электрореактивных двигательных установок на космических аппаратах прикладного назначения // Вестник СибГАУ. 2011. № 2 (35). С. 109–113.

11. Ермошкин Ю. М., Волков Д. В., Якимов Е. Н. О концепции «полностью электрического космического аппарата» // Сибирский журнал науки и технологий. 2018. Т. 19, № 3. С. 489–496. Doi: 10.31772/2587-6066-2018-19-3-489-496.

12. Островский В. Г., Сухов Ю. И. Разработка, создание и эксплуатация электроракетных двигателей и электроракетных двигательных установок в ОКБ-1-ЦКБЭМ-НПО «Энергия»-РКК «Энергия» им. С. П. Королева (1958-2011 г.) // Ракетно-космическая техника. Труды. Сер. XII. Вып. 3–4. С. 122–127.

13. Khodnenko V. P. Activities of VNIIEM in EPT field. History, our days and prospects // 33rd International Electric Propulsion Conference. IEPC-2013-65. The George Washington University. D.C. US. October 6–10, 2013. 19 p.

14. SGEO Electric Propulsion Subsystem Development Status and Future Opportunities / M. De Tata, P. Frigor, S. Beekmans et al. // 33rd International Electric Propulsion Conference. IEPC-2013-144. The George Washington University, USA, October, 6–10, 2013. 11 p.

15. Development of a Solar Electric Propulsion System for the First Brazilian Deep Space Mission / J.L.Ferreira, A.A.Martins, R.A.Miranda et al. // 35th Electric Propulsion Conference. IEPC-2017-166. Georgia Institute of Technology. USA, October 8–12, 2017. 14 p.

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