Developing an inverter controlling electric motor for small air transport

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Abstract. This paper provides a concept for developing inverters for high power aircraft brushless motors. It should be noted that such devices have an increased number of safety solutions, stable rotor synchronization parameters, and an increased number of isolated hardware nodes. The main result of this study is an engine motor controller with a power of up to 60 kW with control through optical fiber, liquid cooling, completely isolated power and control circuits, overcurrent, inverter and motor temperature protection, synchronization by Hall sensors. This paper also contains the calculation of the cost of introducing such solutions into a typical inverter.

1. Introduction

Modern aviation run on electric power is an important and breakthrough technology, which is the future of civilian, industrial and military equipment, both manned and unmanned. A widely used element for creating thrust in electric and hybrid aircraft is a brushless DC motor with a propeller, and a control system, which is a specialized high-power switch with a synchronization device ("inverter"). While developing the inverter, the main attention was on the stability of the technologies used, the reliability of the electronics element base and the minimization of synchronizing circuits. Considerable third party experience in the development of such electronic equipment was taken into account. The developed concept, as well as the model based on it, can be used as part of lightweight manned electric planes or helicopters, as well as heavy-class unmanned aerial vehicles[4] [5].

2. Inverter concept

The initial data for the development of the device was the required continuous developed power on the shaft of up to 60 kW, supply voltage of up to 300V and phase current of up to 500A (not simultaneously). The priority during the development process was the modularity of the solution, the ability to improve the characteristics of the device through the use of a more advanced electronic component base[1]. For that reason, EconoDual 3 [9] form factor modules were selected. Manufacturers produce both IGBT assemblies and silicon SiC-devices in this package. It is important that there is a line of standardized galvanically isolated drivers for them. IGBT modules FF600R12ME4E_B11 designed for peak loads of 600 A or 1200V were used in the developed inverter.

The inverter project was highly inspired by the VESC hardware and software platform, a significant backlog in the field of high-power inverters was obtained by studying and using the achievements of other open projects based on VESC, especially the ones from Palta Tech and Power Designs[2] [8].
When developing an inverter of this type, it is necessary to take into account that in its operating conditions it can be subjected to a number of atmospheric, electrical and mechanical external factors. The created inverter was designed with the ability to withstand high loads, operate in wide temperature ranges, in adverse environmental conditions and with a high level of electromagnetic interference. All of the above can be attributed to normal operation of a small electric or hybrid aircraft[3][4].
In order to meet the operating conditions and to decrease its dimensions, a liquid cooling system was designed for the inverter. However, the design of the inverter allows for air cooling during the testing of the unit.
It was decided to use the Hall sensors method since it is the simplest and most reliable way to synchronize with a rotor of a brushless motor. In addition, the inverter supports sensorless operation and vector field-oriented control (FOC), but these methods are used exclusively for testing the electric motor to obtain its electrical parameters.
The core of the device is done on the STM32F405RGT6 microcontroller from ST Microelectronics. The main device software runs on the ChibiOS real-time operating system. The control unit (electric thrust lever) also runs on this operating system.
The inverter is controlled using an optical fiber wire-isolated thrust lever that transmits a UART signal. Moreover, it can be configured through a CAN bus, which monitors all parameters. Packets for starting and stopping rotation are formed in such a way that reading with an error is excluded. CRC16 checksum accounting is applied. Debugging and testing the system at low power (up to 5 kW) is possible through the USB bus and a personal computer. The system is powered through a galvanically isolated DC / DC converter with an output of +15V, and with a main supply of + 24V. Voltage +15 V is supplied to the drivers of IGBT keys, and in addition, it is converted to power the control part of the inverter, where the microcontroller is located. The advantage of VESC is the end-to-end monitoring of phase voltages and currents in any operation mode of the device, as well as support of advanced control modes: sensorless operation with BLDC and vector control mode (FOC).
The software for the inverter allows you to receive waveforms of phase voltages and currents using the data acquisition module built into the inverter. ADC channels are isolated from the microcontroller to the phases by cascades of operational amplifiers, and then by decoupling amplifiers. The inverter itself is placed in a sealed enclosure with an IP65 degree of protection, which can be assembled in two different ways - with a radiator for air cooling or a panel with liquid cooling channels. During the development process, it was decided to make holes in the case under the IGBT keys for direct liquid cooling. As a result, keys hermetically overlap these holes.
The power supply blocking capacitor for the inverter has been removed from the enclosure. The electrical capacitance must be substantial. It must be at least 400 µF for correct operation. The capacitor block is installed on the inverter supply part to stabilize the voltage and eliminate the influence of reverse currents, which, when working with IGBT, may occur due to the installation of protective reverse diodes inside the modules.
It should be taken into account that the word “inverter” is interpreted not as a frequency converter, but as a control system of a synchronous brushless DC motor.
The image of the three-dimensional digital twin of the inverter is shown in Figure 1.
3. Inverter structural diagram

During development, a typical circuit (Fig. 2.), which contains a three-phase bridge made on IGBT keys with unified drivers was chosen for systems.

A distinctive feature is that the process is controlled through a galvanically-isolated convert UART. In addition, current and voltage are measured at each phase. For current measurement, ACS758-ECB200B Hall effect current sensors are used for measuring currents up to 200A. To expand the range, a 1: 5 shunt is installed on the sensor, which ensures the flow of a fifth of the current through the sensor itself, thereby providing current measurement up to 1 kA. The advantage of using such a sensor is its complete electrical isolation from the power unit which provides remote current measurement.

Voltage is measured through decoupling amplifiers. The power supply for the two decoupled parts of the amplifier is also provided through a galvanically isolated DC / DC converter module.

The diagram shows snubber capacitors for installation on each of the individual switchers. The total blocking electrical capacitance is not shown in the figure.

4. Device prototype

The prototype of the device was assembled in an open design (without housing) on an air-cooled radiator.

At present, the following aims have been achieved:

- operating voltage of up to 100V
- current of up to 40A
- rotational speed of up to 100,000 electric rpm
- PWM frequency of up to 20 kHz

There are tests planned for the near future on a high-power aircraft engine at rated load. A significantly modified version of VESC with the addition of a large number of debugging functions is used as the device firmware. Management is carried out through Vesc Tool 0.95 software, as well as through a UART interface that engages with the electric thrust lever. In addition, telemetry from the developed unit is sent to the network of CAN devices via an isolated interface ISO1050.

The layout image is shown in Figure 3.
5. Economic efficiency of safety components
Galvanically isolated elements are traditionally the most expensive electronic components. Moreover, fiber-optic transceivers and, in fact, the optical fiber itself cost a lot. The most expensive element of the system is isolated IGBT-drivers, which are unified solutions, so it is more inconvenient to develop new drivers than to use these ones. When it comes to the price, the most insignificant part compared to other parts of the circuit diagram is an isolated CAN transmitter.

Table 1 shows the average total cost of installing protected (improved) and standard solutions in the inverter.

| Component                              | Safe component price | Consumer-grade component price |
|----------------------------------------|----------------------|--------------------------------|
| Fiber optic transceiver/ transistor    | 20$                  | 1$x4                           |
| IGBT driver for EconoDual 3/half-bridge driver(i.e. UCC27324D with an isolated DC/DC) | 150$x3              | 20$x3                          |
| Isolated CAN/non-isolated CAN          | 5$                   | 1$                             |
| Fiber-optic wire/ ordinary cables      | 10$                  | 2$                             |
| Power IGBT(or MOSFET) module/ PCB with surface mounted power transistors for the same power | 500$x3              | 300$                           |

Thus, the cost of parts needed to upgrade a typical inverter to an “airplane-safe” one is about $1600.

Table 2 shows the typical cost of inverters of various categories and applications.

Table 2. Typical cost of inverters of various grades
Based on the presented data, improving open source and consumer-grade solutions is economically justified, since the cost of protective safety solutions does not exceed $3000, although it exceeds the cost of the product itself. This figure is close to the average cost of industrial equipment of the required class, but at the same time, such equipment may not have these improvements, except for more powerful power elements.

6. Conclusion
As a result of this study, a design for high-power inverter-control systems for brushless aircraft engines was developed. The assembled inverter model is supposed to be reassembled according to the newly developed design documentation.

Typical elements of the developed design can be used in designing inverters for both light manned aircraft and UAVs with large take-off mass.

The used VESC hardware and software platform has not fully shown its potential for use in aviation technology. In addition, this open project is under development and is now beginning to expand into the field of high-power (more than 4-6 kW) devices. However, it is currently only on the radio-controlled UAV equipment market. The advantages of the chosen platform are: extensibility, rich opportunities for debugging and tuning, a set of both simple and reliable and complex and prospective methods of controlling electric motors.

7. References
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