DESIGN OF A 2300 W 352 MHz SOLID-STATE AMPLIFIER MODULE WITH INTEGRATED ETHERCAT INTERFACE FOR MONITORING AND CONTROL

W.G. Leijenaar†, Leijenaar Electronics B.V , Venray, The Netherlands

Abstract

For multi-unit RF amplifier systems, a 2300 W solid-state RF power amplifier module with integrated EtherCAT and USB interface has been developed. The RF amplifier section is constructed from the latest ART2K5TPU LDMOS from Ampleon with a power of 2300 W at an efficiency of 72 % and is fully shielded and offers space for adding a driver amplifier and phase shifter circuit. The module is equipped with a 7/16 DIN output connector and an N-type input connector and is housed in a metal housing of 200 x 95 x 80 mm. The cooling of the RF LDMOS is done via a CNC milled copper cooling plate that is gold-plated. The gold layer prevents chemical oxidation with other aluminium parts such as an aluminium main plate. In a multi-unit system, the EtherCAT interface provides lightning-fast and synchronous control and monitoring of parameters such as supply voltage and current, heat sink and LDMOS temperature, forward and reverse RF power. Outside the EtherCAT environment, the USB interface can be used in combination with a Windows GUI. Eight LEDs are available as visual indicators.

INTRODUCTION

With the current state of the art of LDMOS transistors it is possible to make large RF powers with a reasonably good efficiency. By connecting amplifiers in parallel multi-kW amplifier systems are possible, but this is not always as easy as it seems. Efficiency is an important parameter which is closely associated with the required cooling. A low efficiency means that more energy is converted in heat, which then has to be removed by a cooling system. Even if an amplifier is optimized on an individual level, a multi-unit system can still perform poorly due to incorrect coupling. Differences in cable losses, phase differences and impedance mismatch can contribute to this. To get the most out of a multi-amplifier system, it is important that each individual amplifier unit can be monitored and controlled, much like a conductor keeping the orchestra playing together in harmony. With the amplifier concept described in this paper an attempt has been made to develop a universal amplifier building block. This has been realized with the latest LDMOS technology in combination with an EtherCAT monitoring and control platform. The system consists only of an RF power amplifier, to which a driver amplifier and phase controller can be added in the near future. These developments are still ongoing and will therefore not be discussed in this paper. It is important to realize that the amplifier concept described here is specifically developed for 352 MHz particle accelerator applications. The modular design still allows it to be adapted for other purposes or with use of other technologies such as Gallium Nitride (GaN). An example of this is a successful 433 MHz experiment with a drop-in GaN device.

Figure 1: Amplifier module seen from the input side (left) and output side (right).

DESIGN CONCIDERATIONS

During the development and testing of it’s 1600 W predecessor, valuable experience was gained in many areas. One of the most important lessons is the careful selection of the uController. Especially in situations with high currents and large RF pulses that we are facing some tolerance against interference is desirable. Therefore, the STM32F103 predecessor was replaced with an ATMEGA1284 processor. The STM32F103 turned out to be very sensitive to external interference and could hang at unexpected moments. Investigation showed that this behavior is addressed in a not easy to find errate [4]. At mechanicall level, the copper heatsink has been further optimized with a better transition from the copper section to the aluminum housing. In addition, a gold plating process is applied to the copper heat sink to prevent the electrochemical reaction between copper and aluminum in humid conditions.

RF AMPLIFIER DESIGN

The RF amplifier is built around the ART2K5TPU transistor in a push-pull configuration that ensures suppression of the even harmonics. Planar PCB baluns are used at the input and output to give a higher degree of reproducibility and is also less labor intensive than the coaxial cable version. The output matching is done with PCB microstrip inductors in combination with mica capacitors. The output PCB is equipped with 70 µm copper to handle the high RF

† info@leijenaarelectronics.nl

currents and reduces the resistive losses. The DC current losses are countered by providing both the push and pull sides with high current supply coils that are connected as short as possible to the LDMOS drain leads. Feeding the high DC current via the RF microstrip traces is not advisable as this will increase the thermal stress on these traces. At the input powers are much lower and the use of ceramic capacitors are used. To get the best possible performance out of the LDMOS it is important to keep the power transistor as cool as possible. To achieve optimal cooling a copper heatsink is used to which the LDMOS transistor is directly soldered. During the initial phase, tests showed that enough cooling could also be achieved using an external water-cooled plate. An integrated water cooling channel would give a fraction more power and efficiency but the added complexity and cost do not outweigh this. As the amplifier unit itself does not have water cooling channels, it is important that the LDMOS transistor is placed as close as possible to the water channel of the external cooling plate. This has been taken into account in the design of the copper heatsink. As can be seen in Figure 2, the LDMOS transistor is placed as deep as possible and soldered directly to the heatsink, further reducing the thermal resistance. For thermal management this is the best we can do, but from an RF perspective it creates many problems as the input and output planar balun designs require a cavity. A solution was found by having the input and output circuits made in an angle. This brought many challenges to the design of the copper heatsink in terms of manufacturability. The performance of the RF amplifier mainly depends on this optimized heatsink design.

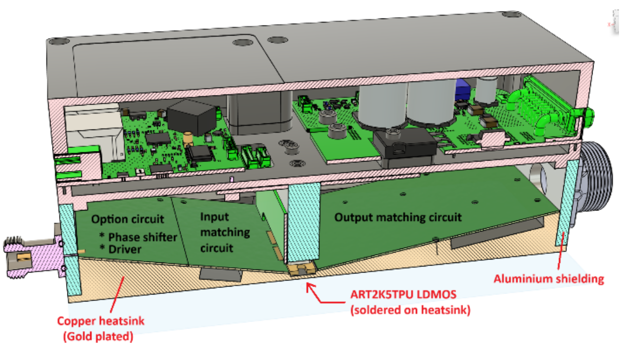

Figure 2: Cross section showing the LDMOS RF transistor located in the copper heat sink valley.

The manufacturing of the copper heat sink is done with utmost precision and craftsmanship. A good efficiency is next to RF output power the most important parameter. This not only leads to a reduction of the electricity bill, but also in the reduction of stress on components and water cooling installation. High currents are associated with cable losses. It is therefore essential to keep cable resistance low and cable lengths short. It starts with the DC connector that has to have a low enough contact resistance to supply the maximum required current of 40 Ampers during CW operation. The large currents are led to the LDMOS RF transistors via the shortest possible path. To handle the high RF output power a 7/16 DIN connector was choosen. With more than 3 kW of RF power capability at 350 MHz the 7/16 DIN connector offers more security than the 2 kW power capability of an N connector. The risk of sparking or overheating is thus eliminated. A fully RF-tight metal housing ensures that virtually no RF energy can leak out. Special attention has been given to the passage of the DC power lines and the signal lines for the bias and sensors. Standard DC connectors require an opening in the RF shielding which causes significant electromagnetic leakage. In order to minimize RF leakage, a cleverly designed multi-layer pcb has been made which, in addition to RF shielding, also provides some RF decoupling.

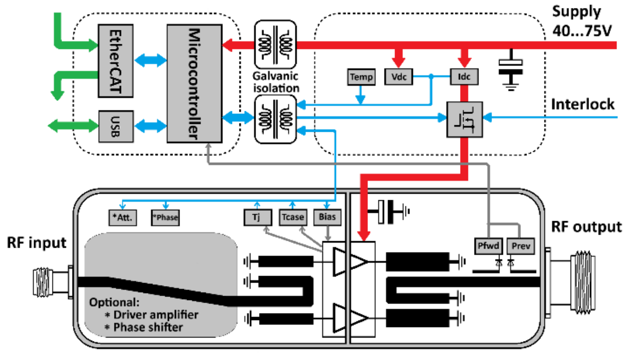

Figure 3: Inside schematics of the amplifier module.

ETHERCAT INTERFACE

To make hundreds of amplifiers work together in harmony it is essential to monitor and control each of them individually. For monitoring and controlling a large number of units a kind off network system is required. Since everything is connected in parallel, it is essential that this network is extremely fast and synchronously. One of the network systems that is suitable for this task is the EtherCAT system. EtherCAT is an Ethernet-based fieldbus system developed by Beckhoff Automation that uses standard Ethernet cables, resulting in cost savings. Monitoring is important to keep all parallel connected amplifier modules running in full harmony. Parameters such as supply voltage, supply current, temperatures and RF powers are tracked with precision time-stamps. Active control allows amplifier modules to be controlled both individually and in groups. On an individual level a module can be corrected if it gets out of sync or switched off in the event of thermal runaway. At system level EtherCAT makes it possible to switch all amplifier modules on at the same time with high precision. Other variation are also possible, for example by having amplifier modules in standby to switch over to in the case one of the operating amplifier modules fails to work. Another reason could be to make periodical maintanance posible in a 24/7 system. In addition to the desire for the highest possible power and efficiency it is of great importance to ensure safety. This is both for the human beeing and the system itself. Besides acting on an event we also need to look for signs of a slowly failing module. Most failures are caused by a gradual loss of certain parameters like the increase in temperature, which could eventually result in a catastrophic breakdown. In order to prevent a breakdown event we will monitor all amplifiers in detail. This allows the monitoring computer to detect potential weak modules and flag them for maintenance, or turn that particular module off and switch over to a standby module. In the event that one of the RF amplifiers stops to work, it's EtherCAT controller system should still be able to function and keep the EtherCAT communication alive. This is guaranteed with the build in galvanic isolation of the control unit, shown in Figure 3. The galvanic isolation prevents large DC and RF currents from finding a way through the control and EtherCAT system.

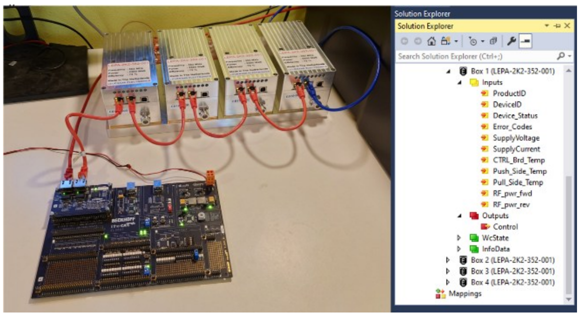

Figure 4: A small EtherCAT network consisting of four amplifier modules and a Beckhoff development board (left side). TwinCAT snapshot showing the EtherCAT slaves (right side).

USB INTERFACE

Although the EtherCAT interface offers many advantages in a large network environment, it is less convenient to use during maintenance and production testing. For this special purpose a USB interface is built in which allows direct access to the stand-alone module. A Windows Graphical User Interface (GUI) is created for USB access which allows the operator to monitor all sensors and also allowing to change settings such as bias voltage and activating the LDMOS transistor. During production this USB interface offers the flexibility to program calibration values for the various sensors and to perform internal tests.

INSTALLATION

Sometimes hundreds of modules need to be mounted in a larger system, often in places with limited mounting space. A design that requires access to the internals is extremely risky. Possible damage to the electronics or a forgotten screw causing a short circuit can be catastrophic. The amplifier module is therefore completely sealed and can be mounted on a cooling plate from the outside using six screws. Two of those screws are located very close to the LDMOS RF transistor to force a good thermal connection to the cooling plate underneath. The 95 mm module case width allows modules to be mounted tightly next to each other at 100 mm intervals. This modular concept makes the development and production of a multi-unit system quick and easy, ultimately contributing to cost savings.

KEY FEATURES

The most important feature is the combination of a state-of-the-art RF amplifier with the fast and time-accurate EtherCAT system. This makes the design extremely flexible and usable for a variety of configurations. Other key features are listed in Table 1 below.

Table 1: Single module key features

Operation mode	Pulsed, CW
Frequency	352 MHz (± 1 MHz)
Gain (P3dB)	18 dB
Output power (P3dB)	2300 Watt nominal
Efficiency	72% nominal
Spur levels	2f0 ≤ -35 dBc 3f0 ≤ -45 dBc
Connectors	Input: N-Female Output: 7/16 DIN DC: SUBD 17W2
Parameters monitored	Vdc, Idc, Pfwd, Prev, Temp: heatsink, LDMOS
Parameters controlled	RF on/off, Vbias
Cooling	By means of convection
Method of mounting	6x M4 bolds

FUTURE AND ONGING WORK

Extensive testing in a larger, multi-unit system will still need to be performed in conjunction with scaling and expanding the EtherCAT interface software, such as precision timing and processing of the large amount of real-time data. At the time of writing, there is a development going on for a driver amplifier with integrated phase shifter. The goal is a stepless electronically controlled phase shifter, which at the moment cannot be achieved with off-the-shelve parts due to the power handling restrictions.

CONCLUSION

A 352 MHz amplifier module has been developed that can be used flexibly in multi-unit amplifier systems and thus significantly reduces the development time and development costs of such systems. In addition to the increased 2300 W with an efficiency of 72%, all controls and interfaces are integrated in this module to obtain maximum performance and safety from a multi-unit system.

REFERENCES

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