

HIGH-EFFICIENCY INDUSTRIAL 130 KW CW SOLID-STATE RF AMPLIFIER FOR 1.3 GHZ

M. Nedos, N. Pupeter, V. Wied, Cryoelectra GmbH, Wuppertal, Germany
B. Keune, C. Quitmann, G. Blokesch, RI Research Instruments GmbH, Bergisch Gladbach, Germany

Abstract

A new 1.3 GHz solid-state high-power RF amplifier (SSA) has been built for the Lighthouse project in close cooperation between Cryoelectra and RI Research Instruments. The amplifier was developed by Cryoelectra as a scalable compact system with an RF-power density of 40 kW/m². Its industrial design is very reliable and easy to maintain. The SSA delivers a continuous RF output power of more than 130 kW with a wall-plug efficiency of 63% and with very low phase noise. The power is generated by 40 patented RF amplifier modules each containing 8 GaN transistor units. Their outputs are combined by a coaxial 8-way combiner in the center of the module. Each module is connected to the 4x9-way cable-free waveguide combiner network and can be exchanged in the event of fault within minutes thanks to quick connectors. A sophisticated control system continuously monitors the state of all components for reliable machine and personnel protection. Despite all the challenges encountered during development and production, the SSA was built and handed over to the client in the shortest possible time. It passed the acceptance test on site exceptionally well.

STRUCTURE

As with any transistor based high-power RF amplifier the working principle lies in the parallel operation of many transistors - in this case 288 for the final stage alone. Their outputs are connected to a multi-stage cable-free combining network ending up in one big RF waveguide output. Since every transistor needs a separate input signal a similar structured network is used for splitting. To achieve the high power gain, a pre-driver and four drivers are integrated at different stages of the splitting network. [1–3]

The main building blocks of the SSA are the RF modules in the world-wide patented tower module design (see figure 1), each containing eight power transistors. The RF module provides the infrastructure necessary for the transistors operation, like cooling, DC power, and monitoring. Both, an 8-way splitter and an 8-way combiner are integrated in the RF module.

The transistor supply voltage is generated by 80 off-the-shelf conduction-cooled rectifier modules, each delivering up to 3.5 kW of DC power. These power supplies achieve a very high AC-DC efficiency of 96% peak at 50% load. Like the RF transistors, the rectifier modules are mounted on water-cooled cold plates to dissipate the heat generated. Since the cooling circuit consists only of copper and stainless steel, the cooling medium can be either deionized water or tap water.



Figure 1: The CRE-350D-1 RF Module (cover removed).

All described components are continuously monitored by the control system to ensure a safe operation. Heart of the control system is a Programmable Logic Controller (PLC) to which all sub-controllers are connected. The monitored parameters are transistor voltage and current, RF module heat sink temperature, power supply temperature and DC output power, cooling water temperature, water flow, water pressure as well as forward and reflected RF power measured at several stages of the combining network. In addition to the internal event detection by the control system, the fast RF gate at the input of the amplifier can be closed by the external interlock in less than one microsecond, which is required to safely shut down the 6 MW electron beam in case of emergency.

EFFICIENCY

A high wall-plug efficiency (i.e. RF output power over AC input power) is becoming more and more important these days. Even an increase by 2% can save 50 000 kWh of energy per year for this amplifier, which corresponds to a saving of 400 000€ during a required lifetime of 25 years¹. We have identified several sources of efficiency loss. The values have been calculated at the 1 dB compression point (P1):

- AC-DC conversion 4% to 8%,
- Driver 2% to 3%,
- RF Transistor 23% (GaN) / 42% (LDMOS)²,
- Circulator on RF unit 2%,

¹ Assuming 8400 h of operation @ 130 kW per year and 0.32€ per kWh. The difference from 63% to 65% efficiency would be 206 kW - 200 kW = 6 kW of AC power. The long service life of 25 years is to be achieved by a reliable design, continuous quality monitoring during production and an appropriate maintenance concept.

² Gallium Nitride (GaN) / Laterally Diffused Metal-Oxide-Semiconductor (LDMOS)

- Combining Network 1% (current combining scheme) / up to 5% (standard combining).

Since the main efficiency losses are determined by the transistor and its technology, nearly 20% of efficiency increase have been achieved by using GaN transistor technology with respect to available LDMOS transistor based solid-state amplifiers for this frequency. [4]

As shown in figure 2, the efficiency depends on the RF output power for a given transistor drain voltage. To operate the amplifier at the point of highest efficiency even at lower output powers, the drain voltage can be decreased to move the 1 dB compression point to lower powers and increase the efficiency. This we call P1 control. The presented amplifier covers an optimal operation range from 70 kW up to 140 kW with efficiencies higher than 60%. This corresponds to a transistor drain voltage range of 36 V to 53 V. The drain voltage can be changed by the remote control system at any time.

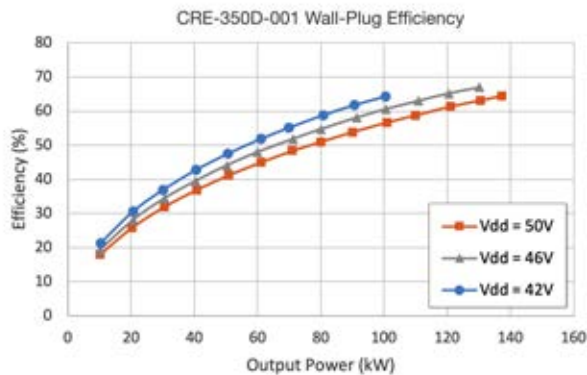


Figure 2: Wall-Plug Efficiency vs. RF Output Power and Transistor Drain Voltage.

Another 4% of efficiency was achieved by using a combining network of tower module and waveguide combiner (efficiency loss only 1%), in comparison to a standard combining with strip-lines, RF cables and coaxial combiners.

RELIABILITY

To design an amplifier for a 24/7 operation, one has to consider the mean time to failure (MTTF) for the components used, the operation parameter space for these components and the degree of redundancy. An MTTF evaluation has been done for all active power parts. If available, components with higher MTTF values have been selected. As an example, instead of air-cooled power supply modules we have selected a conduction-cooled type, since the latter one has a 7-times higher MTTF. When comparing LDMOS and GaN transistors, the differences are even more impressive. In addition to the higher efficiency, the GaN transistor also has a three order of magnitudes higher lifetime, as calculated by the manufacturer for the use case with 2×10^{10} hours. Another part of the design work went into optimizing the operating parameters in order to keep the thermal load on

the components as low as possible. This further increases the MTTF. For the RF transistor unit the right printed circuit board (PCB) material with high thermal conductivity has been selected and a sophisticated brazing technique has been used to solder the whole unit on a heat sink. As a result a very low operating temperature has been achieved for the transistor, each generating 500 W of RF output power. The transistor cap temperatures of three RF units measured during the fabrication test are shown in figure 3. Since the die temperature cannot be measured directly, the cap temperature is observed instead, with $T_{die} \approx 1.7 \times T_{cap}$.

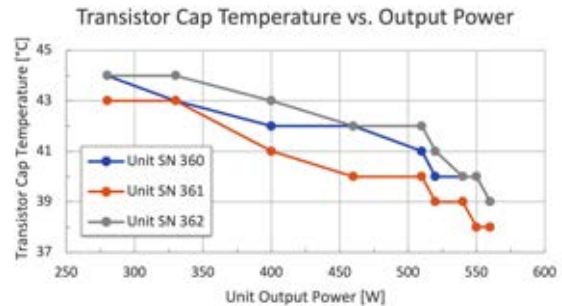


Figure 3: Transistor Cap Temperature during Operation.

If a component fails despite the great care taken in the design process, the amplifier can continue running due to the redundancy of all active power parts. Single points of failure have been avoided in the design wherever possible. The DC outputs of all power supply modules of the same cabinet are combined on one common copper busbar before distribution to the RF modules. With a redundancy of 25% this allows a failure of 5 power supply modules per cabinet without having a reduction of the RF output power. For the RF transistor units, the redundancy is obtained through the combining network. The failure of one transistor unit results in a loss of double the power each remaining transistor unit generates. 100% because of the missing transistor unit and another 100% due to all arising mismatches in the combiner system (thanks to the circulators without damaging influence on the active transistor units). An operation at 130 kW RF output power will be still possible, even if 10 transistor units have failed. If more components are failing, the output power is gracefully degraded.

MAINTAINABILITY

In case of a fault the control system identifies the broken component and indicates it on the graphical user interface (GUI) of the remote control system. Due to its industrial design, nearly all components of the amplifier are easily accessible and replaceable within minutes. This will keep down times at a minimum. The DC power supply modules are hot-swappable and could be replaced during operation. The RF modules are equipped with quick connectors for the cooling water supply, the DC voltage supply and the RF output³. An indicator next to the module lights up, when the

³ Water: Walther Präzision, DC: Stäubli Multicontact, RF: 3 1/8" EIA

module is correctly inserted.

In case the failure cannot be corrected or found within the maintenance period, each of the four RF station cabinets of the amplifier can be replaced as a whole within two hours. In this way, an SSA downtime of more than two hours can be avoided, even in the case of the most complicated RF station failure, provided a backup RF station is available. This is of special importance, if a series of these amplifiers is used.

OUTPUT PURITY

Due to several design techniques, very low phase and amplitude noise values have been achieved for this RF amplifier. A major source of the noise is the DC power supply. The selected power supplies have intrinsically small output ripple voltages⁴ and are internally buffered to compensate changes in the mains supply line. Since the internal switching clocks of the power supply modules are not synchronised, any interference remain in the noise floor and does not build up to a spurious signal. Furthermore, the common copper busbar for DC distribution is capacitor buffered with 100 mF against its return line. On the individual transistor unit each current line is additionally buffered with 470 μ F. Close to the transistor, at the RF choke, a final buffering for fast and small ripples is integrated using two very low equivalent series resistance capacitors of 47 μ F.

Another characteristic of solid-state RF amplifiers are the content of higher order modes (harmonics). They are produced as soon as you operate a transistor in the output compression region, where you have the highest efficiency. The output matching circuit and the combining network can act as a filter suppressing the harmonics content. Figure 4 shows the suppression for the 2nd and 3rd harmonics for the presented amplifier. Furthermore, the frequency range around the carrier must also be checked for unwanted signals generated by the amplifier. This test did not show any spurious content on the output signal at the nominal output power of 130 kW..

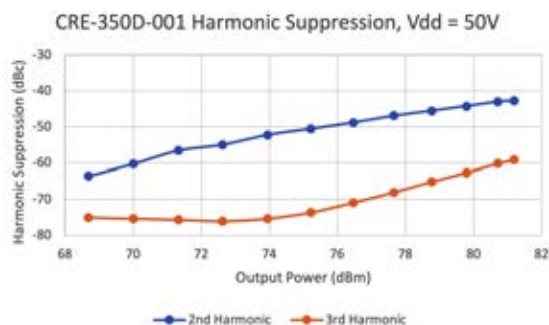


Figure 4: Harmonics Suppression at the SSAs Output

⁴ within 20 MHz bandwidth - ripple: 0.2% (rms), noise: 1% (pk-pk)

CONCLUSION

The featured amplifier is at the forefront of today's high-power solid-state RF systems. Thanks to the usage of GaN transistor technology, a superior wall-plug efficiency of 63% has been reached. The amplifier is designed for a 24/7 operation, which was achieved by a careful component selection, rigorous design work and the implementation of adequate redundancy. The amplifier has been extensively tested at the factory under full output power and is waiting for a new mission.



Figure 5: CRE-350D Solid-State Amplifier during Factory Acceptance Test on a Water Load

REFERENCES

- [1] A. Grebennikov, "RF and microwave power amplifier design", USA: The McGraw-Hill Companies, Inc., 2005.
- [2] T. Ruan, "High Power Solid state amplifiers for the SOLEIL Synchrotron", presented at The Fifth CW and High Average Power RF Workshop, CERN, 25th Mar. 2008, <https://indi.to/thD4W>.
- [3] J. Jacob, "Radio Frequency Solid State Amplifiers", contribution to the 2014 CAS - CERN Accelerator School: Power Converters, Baden, Switzerland, 7-14 May 2014, arXiv:1607.01570.
- [4] R. G. Heine and F. Fichtner, "The MESA 15 kW cw 1.3 GHz Solid State Power Amplifier Prototype", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4216-4218. doi: 10.18429/JACoW-IPAC2018-THPMF063