Operational Experience of Solid-State Replacement for Hard Tube Modulators

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Air defense radar systems in the medium power class (approximately 125 kW average power) have been in service for over thirty years. These legacy systems are based on physically large vacuum tube switching components facing obsolescence in the manufacturing world. To address component availability and reliability, new solid-state replacement modulator designs have been deployed in a number of systems in the Europe NATO backbone air defense system. The early operational experience of these modulator system upgrades has been positive and has demonstrated operational integrity and system reliability improvements at the installed sites. A system description of the replacement modulator and some fundamental performance will be presented. Early reliability performance data will be discussed as well as potential improvements for increasing the system availability to even higher levels.

Keywords—modulator, solid-state, medium power, klystron, radar, high voltage, pulse, RSRP, power supplies, power system reliability, transmitter, hard-tube

I. Introduction

Since the early days of radar systems, hard tube modulators have been one type of power train topologies for producing high power pulsed microwaves [1]. As the average power levels of these systems increased over time, the power train designs continued to use vacuum tubes (hard tubes) as the primary controlling device. In recent years, solid-state devices have been used to replace vacuum tubes as the primary controlling modulator device and have improved reliability of these systems.

A solid-state modulator upgrade to the Radars for the Southern Region and Portugal (RSRP) is in progress. These are shelterized, transportable, early warning, medium power, long range, phased array mono-pulse systems with electronic scan in elevation of the search beam used in the Europe NATO backbone air defense system. The need for the replacement of the hard tube topology has been driven by recurrent obsolescence cases which until now have been resolved on a case by case basis resulting in increased maintenance costs.

The solid-state modulator topology is based on a patented design [2] of a modified Marx modulator [3,4]. In this topology, a number of modular stages are connected in parallel during the intra-pulse charging period and are then connected in series to produce the high-power beam pulse to the microwave amplifier. The modular stages also provide a level of redundancy and graceful degradation, allowing for system repair and maintenance to be scheduled at non-critical operational periods. Reducing the number of single point failure components in the system has led to improved operational availability. Thus, this solid-state modulator topology represents an attractive replacement solution with an operational availability and mission critical response equivalent to the more expensive active phase array systems.

This paper describes the solid-state modulator system, early performance and future plans.

II. System Description and Performance

There are four main components to the solid-state modulator system, the: 1) Power Rack, 2) Modulator Control Unit (MCU) Cabinet, 3) Modulator Cabinet and 4) Klystron Tank as can be seen in the outline drawing in Fig. 1. The modulator and the power supplies are water cooled. The only oil in the system is in the Klystron Tank, containing less than 124 liters of FR-4 type oil.

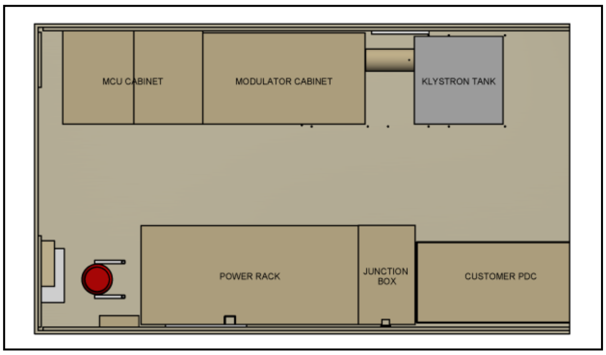

Fig. 1. Outline drawing showing the four main components of the solid-state modulator.

Power is delivered to four 50 kW, 3 kV charging power supplies (located in the Power Rack) that are able to operate in parallel and independently, providing for redundancy at this point in the power train. Using advanced control methods, these charging power supplies can maintain regulation over large variations in output duty cycle providing repeatable pulse-to-pulse radar beam performance.

The solid-state Marx modulator comprises of multiple stages of identical modules. These modules are interchangeable and can be placed in any of the positions in the cabinet. Fig. 2 shows the switch modules inside the cabinet and that they are easily removed by loosening two bolts and sliding out the module. The modulator has been designed to keep running at full output power with up to 10% of the switch modules failed, so the replacement of failed switch modules can wait until the next planned maintenance or when the radar maintenance downtime is granted.

Fig. 2. Marx switch modules inside the cabinet.

Between radar pulses, each stage connects in parallel with the other stages to allow for rapid recharging of their energy storage components. During a radar pulse, the stages connect in series, discharging some of each module's stored energy and produce a high-power pulse into the system microwave amplifier. A typical pulse current waveform is shown in the oscilloscope trace of Fig. 3. During this relatively long radar pulse, the current only droops to 98% of the initial amplitude. The duration of this high-power pulse can be continuously adjusted from 10 to 110 microseconds. This feature combined with the ability to continuously adjust the Intra Pulse Period (IPP) provides for extremely agile radar performance. Fig. 4 shows a random oscilloscope snapshot of a pulse train, demonstrating that the pulse duration and IPP can change on a pulse to pulse basis.

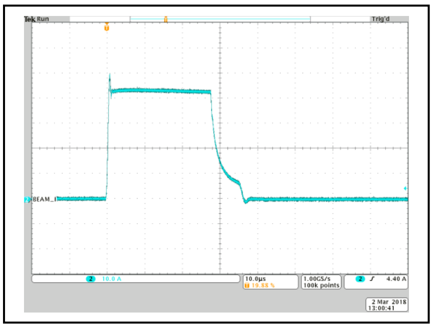

Fig. 3. Oscilloscope trace of a 30 us current pulse.

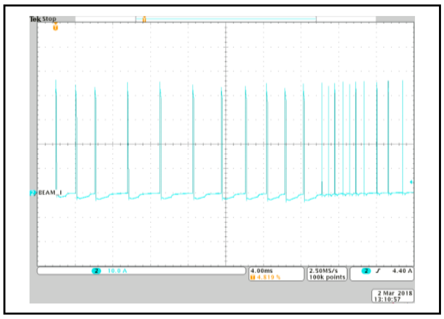

Fig. 4. Oscilloscope snapshot of a pulse train.

Operational average power varies from 100 kW to 200 kW during duty cycle variations in the output radar format. Maintaining pulse-to-pulse amplitude stability while adjusting to the agile pulse format and duty cycle is a key metric for system performance. Fig. 5 is a screen shot from the Transmitter Control Unit (TCU). It shows a pulse-to-pulse amplitude variation of 1.2 A over an instantaneous duty cycle variation from less than 1% to 5.3% for transmitting the beam for one elevation scan. The cathode voltage pulse-to-pulse stability for the Moving Target Indicator (MTI) beams is better than 50 V, with an improvement of the overall system stability of nearly 3 dB as measured by performing Clutter To Noise Improvement Factor Tests at the Radar Signal Processor (RSP) [5].

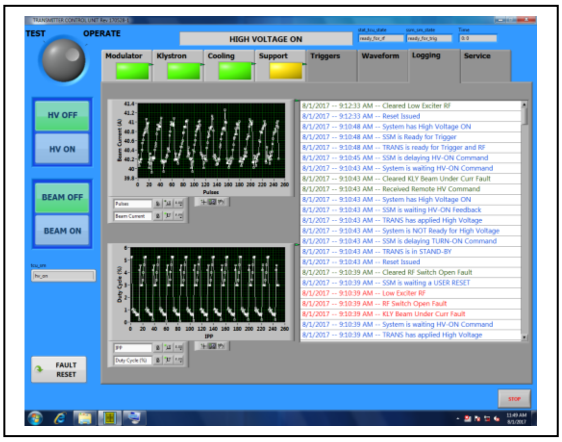

Fig. 5. Screenshot of the TCU showing instantaneous duty.

III. Integration of the Solid-State Replacement into the Shelter

To date, modulator upgrades to three operational RSRP radar sites have been completed. Six more upgrades are forecast in 2018 and 2019. Fig. 6 is photograph of the solid-state modulator installed in a shelter. Fig. 7 shows the legacy modulator installed in a shelter. The upgrade is a mechanical and electrical drop-in replacement, with no impact to the existing radar and transmitter interfaces, as well as, occupying the same volume of the replaced modulator, minimizing the integration costs.

Fig. 6. Solid-state modulator installed in a shelter

Fig. 7. Legacy modulator installed in a shelter.

IV. Advantages of Marx Solid-State System Over the Legacy System with Vacuum Tube Switching

The legacy modulator system comprises an oil insulated pulse transformer containing 364 liters of oil with a 124-liter transmitter tube socket and an oil insulated 48 kVdc power supply containing 660 liters of oil. The transmitter socket oil is field replaceable. The oil for the pulse transformer and the power supply is not field replaceable and requires shipping those units to qualified facilities to properly repair and process the oil for those components. The solid-state replacement system only contains oil in the 124-liter transmitter tube socket. This eliminates the shipping of large components containing oil for repair.

The legacy system also has a number of single point failure components that can prevent operation even in critical mission time periods. If any one of these components fails during a critical mission, the system goes off line and must be serviced to bring it back into operation. The solid-state modulator replacement system has been designed with a level of redundancy, allowing operation during critical missions even if a component failure has occurred. This keeps the system operational when needed and allows the system operator to determine the appropriate time to perform any required maintenance or repair.

An added benefit is that the solid-state modulator is inherently safer and at less risk for faults in stand-by because the stand-by voltage is only 3,000 Vdc as compared to 48,000 Vdc in the legacy system. The significantly higher voltage of the legacy system stresses the air insulation of the vacuum tube area and requires periodic maintenance to keep insulators clean.

To improve field serviceability, the field replaceable unit for the solid-state modulator system was designed to be smaller and modular. This reduces field service stocking requirements and system repair durations. Additionally, the modularity and redundancy with graceful degradation allows for planned maintenance even when a component failure has occurred. Designing with maintainability and reliability as well as performance improvements in mind provide a significant improvement over the legacy systems.

V. Pre-Active Radar Testing

The first production modulator was installed in Luxembourg in a system which was going to be upgraded before its relocation to a new operational site, thus allowing any installation and integration challenges to be worked out before disrupting an operational radar system. Operational tests were conducted on the system for 14 months.

VI. Early Reliability Performance Data and Analysis

The first installation in an active radar was in 2016 in Portugal. That system has logged 11,000 operational ours. There have been three switch module failures and three blower failures.

The second installation was in Greece in 2017. This system has logged 6,500 operational hours. Two switch modules and one blower have failed.

The third system upgrade was also in Greece in 2017. This system has logged 4,000 operational hours. One switch module has failed.

It is not clear yet the root cause of the switch module failures or whether there is one point of failure. Not all failed modules have been returned yet for an analysis. There are thirty modules per system. With six switch module failures over a total of 21,500 system operational hours (equating to 645,000 switch module hours), the switch module failure rate is 9.3 failures per one million operational hours.

Three of the four blower failures have been a particular blower in the modulator cabinet. There are two blowers of the same type in the cabinet and all the failures have occurred in the one near the high voltage connection between the modulator and the klystron socket. It has been determined that the failures are due to high electric fields. The fourth blower failure was in the power supply rack and at present the cause is unknown. The blowers can be considered a critical failure because they provide necessary airflow and cooling inside the cabinet. Blower failures are monitored and reported as a cooling fault, causing the transmitter triggers to be inhibited.

In total, the modulator system upgrade critical failure rate is 186 failures per one million operational hours. The non-critical system failure rate is 279 failures per one million hours.

VII. Improvements Planned and In Process

The switch modules are not considered a critical failure because the system can continue to operate at full power with up to three failed switch modules. In light of the fact that it is a non-critical failure no improvements are planned until we have more failure analysis data.

A redesign effort is underway to move the failed blower out of the high field environment. Airflow to the desired area will be accomplished through ducting inside the cabinet.

VIII. Conclusion

The solid-state modulator replacement shows great promise in early operational experience. Three operational systems are demonstrating excellent reliability and improved operational availability over the legacy vacuum tube system due to its graceful degradation.

Further advantages are the drastic reduction of the total transmitter parts count, alignment procedures necessary to maintain the expected transmitter stability and the ease of troubleshooting in case of failure.

The redundancy of the modulator switch modules and power supplies is expected to decrease the future maintenance costs and extend the operational life of the radar.

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