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TRENDS IN RF TECHNOLOGY FOR APPLICATIONS TO LIGHT SOURCES WITH GREAT AVERAGE POWER

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Abstract

RF systems are a major part of both the capital and operating costs of contemporary light sources and directly impact their capability, reliability and availability. The RF community has been discussing for many years the best choice of CW RF power source for light sources. In the domain of great average power, the choice is among a klystron, inductive-output tube, and solid-state RF amplifier. Here we review their current development and challenges and offer a perspective from a point of view of operating a light source with high reliability and availability.

INTRODUCTION

A modern synchrotron light source pursues machine operation with great reliability and availability to satisfy the rigorous experimental demands of its users. Two merits, the *availability* and the *mean time between failures* (*MTBF*) of the machine operation during the scheduled user beam time, are commonly adopted to reflect the integrated operational performance of a light source. From the point of view of a user, the MTBF is even more relevant, but it is difficult to improve this significantly in a period short relative to the availability of beam time. An analysis of the statistics of machine operation shows clearly that roughly half the trip rates arise as a fault of the RF system of a light source as its operation becomes mature. Whether the RF system of a light source is reliable and available is consequently crucial for the operational performance of a light source.

A high-power RF source, even it is mostly an industrial product and commercially available, can still become a bottleneck of machine operation if it has not been properly selected or designed to be reliable and available for operation under a large average power. An RF source can be extremely reliable if it is designed over specification, implemented with *N*+*n* redundancy to allow hot swapping over a fault module and maintained in a preventive way, which implies a capital cost, system complexity and extra maintenance effort. Implementing advanced diagnostic instruments and using automatic fault-logging software is certainly helpful to decrease the period required for troubleshooting.

Klystrons, inductive-output tubes (IOT), and solid-state RF amplifiers are the most popular high-power RF sources for a modern light source. Several review papers and talks have addressed this topic [1-5]. Here we review their present development and challenges, and offer a perspective from the point of view of operation of a light source in a highly reliable and available manner.

KLYSTRONS

High-power klystrons at frequencies of most interest for the light sources, mainly 352.2 MHz and 500 MHz, are commercially available from a few manufacturers of vacuum-electronic devices that monopolize the shrinking market restricted to scientific applications. Their price consequently increases steadily, for example at a rate about 5 % annually in the past ten years continuously for some popular product with limited quantity of procurement. A klystron might eventually become difficult to obtain in the market at a reasonable price.

The capacity of a klystron of existing design might fit imperfectly the special needs of a light source. The development of a new klystron is not only costly but time-consuming, which is obviously beyond the scope of its application to a light source. Powering a light source with a klystron of excess capacity causes unreasonable capital and operational costs. Distributing the RF power from an over-scale klystron simultaneously to a few RF cavities increases the complication of RF control and is no longer a popular option adopted for modern light sources. Modifying an existing under-capacity klystron to meet the special need of a machine operation risks ensuring a satisfactory operational performance because operational experience is lacking. For example, the 100-kW klystron used for Taiwan Light Source is an upgraded version of a 70-kW klystron designed for a television station, and is operated in an over-voltage mode but with a newly designed full-power collector and output coupler. Its maximum output power nevertheless becomes extremely sensitive to the degree of load mismatch that is mostly difficult to perfect in practice, restricted by the performance of a high-power circulator, etc.

A klystron requires a large DC voltage for example, -23 kV for 70 kW, -27 kV for 100 kW, and -53 kV for 300 kW RF output. The high-voltage power supply is classically equipped with a crowbar circuit to ensure a quick dump to ground of the stored energy from the high-voltage power capacitor, which is part of the choke filter, to protect the klystron from damage during, for example, internal arcing. A high voltage can alternatively be generated by a superposition of a few tens of switching power-supply modules using an insulated-gate bipolar transistor (IGBT) as a rapid switch. A high-voltage power supply of the so-called pulse-step modulation (PSM) type benefits the design with *N*+*n* redundancy and allows hot

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swapping from a PSM module to another that makes a high-voltage power supply of this kind extremely reliable. The PSM-type high-voltage power supply has become, in the past 15 years, equipment more or less standard for a light source using a klystron or IOT as an RF source. Furthermore, a high-voltage power supply of the PSM type allows a freely adjustable high voltage in a wide range required for klystron operation, which is unrealistic in practice for a high-voltage power supply of crow-bar type. The efficiency of a klystron is readily re-optimized on tuning the klystron cathode voltage together with the cathode current, whenever the operation requires a decreased maximum RF output power. On the other hand, the high-voltage power supply of PSM type generates RF noise from its rotation of the PSM modules and from the harmonics of electric power. A coincidence of the rotation frequency with the synchrotron oscillation frequency of the storage ring is avoidable on varying the switching frequency of the IGBT. Harmonic sidebands can be minimized after proper correction with software, but their contamination in the infrared beamline remains a major concern [6] that might be cured with a digital low-level RF system.

The high-voltage components require operation in a dry (low humidity) and clean environment. If any high-voltage component becomes weak, the high-voltage power supply becomes less reliable, which is difficult to clarify in a direct manner for a high-voltage power supply equally of either crowbar or PSM type. A high speed multi-channel transient recorder with large memory is useful to identify the signal of a first trip. A regular high-voltage test to evaluate an increased leakage current under high voltage as an index of preventive maintenance improves the operational reliability. Selecting high-voltage components over specification significantly extends the operational lifetime and decreases the maintenance effort. A safety factor 1.5 ensures a smooth operation, as verified from the RF transmitter of crowbar type used for Taiwan Light Source. Its operational statistics accumulated from 2005 shows a MTBF more than 930 h. The average annual scheduled user beam time is greater than 5300 h.

INDUCTIVE-OUTPUT TUBES

The inductive-output tube (IOT) is a hybrid of a grid tube and a klystron. The velocity modulation is effected with a grid similar to that of a triode, and the density modulation and RF output are similar to those properties of a klystron. Like a klystron, an IOT relies on the support of a high-voltage DC power supply to generate an energetic electron beam. The HVPS of PSM type has become popular for reasons similar to those cited above for a klystron-based RF transmitter. An IOT has consequently a travel of the beam from its cathode to the collector shorter than that of a klystron. This condition relaxes the degree of contamination in its RF output for a given ratio of high- voltage ripples from its high-voltage DC power supply. A klystron is much more sensitive to high-voltage ripple than an IOT. The physical dimensions of an IOT are generally much smaller, and its weight much less, than a klystron with a similar rating of maximum RF output power. These properties certainly simplify its replacement effort relative to a klystron. As an IOT has a small gain, about 20 dB, but a klystron has a large gain, up to 40 dB, the RF drive power for an IOT must be much larger than that required for a klystron.

A klystron has a saturated efficiency up to 65 %, or even more, but operating the klystron under saturation makes its drive control difficult or complicated because of its marginal positive differential gain. The operational efficiency of a klystron decreases further when the feedback loops to control the RF output require operation of a klystron with a considerable positive differential gain. An IOT can have an efficiency approaching 70 % at its maximum RF output power with sufficient positive differential gain to maintain its regulation. An IOT also maintains its great efficiency at a decreased maximum RF output power over a wide range of operational interest. The IOT has consequently replaced a klystron and has become widely used in UHF TV applications.

An IOT that features great efficiency is attractive also to light sources to decrease the operational cost. The Diamond Light Source (DLS) first decided to select IOT as RF sources for operation of storage ring [7]. An IOT with maximum RF output power larger than 100 kW is so far commercially unavailable. A multi-beam high-power IOT must have the potential to deliver a few hundred kW with a small cathode voltage, but is not yet commercially available. Combining a few IOTs to deliver a higher RF output is hence required. The 300-kW RF power required to operate individual 500-MHz superconducting RF modules of CESR type at DLS is obtained on combining four IOTs, each producing maximum RF output power 80 kW [7]. Italian light source Elettra combines two 80-kW IOTs for maximum RF output 150 kW at 500 MHz to operate its individual RF cavities of Elettra type [8]. Similarly, Spanish light source ALBA combines two 80-kW IOTs to deliver maximum RF output power 150 kW required to operate its individual 500-MHz EU cavities for the storage ring [9].

The IOT adopted for booster RF operation has demonstrated its superiority, in that it does not require operation with a large average RF power relative to its maximum operational RF output power, similar to its application in television transmission. A light source nevertheless requires operating IOT continuously near the maximum RF output power to operate its storage ring. This discrepancy in operational requirements eventually degrades the operational reliability, and hence decreases the operational lifetime. Furthermore, an intensive effort becomes routinely necessary in the RF conditioning of the troublesome IOTs. The experience of IOT so far, with CW operation [10-12] is much less than that of a klystron with its abundant statistics. A continuous feedback from users of its light sources and an improved specification by the manufacturers will eventually overcome this particular weakness. Before an IOT becomes absolutely superior for its application to a light source, operating an

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IOT with a design over specification is still an option for a light source to benefit from its high efficiency but with acceptable reliability and lifetime.

SOLID-STATE RF AMPLIFIERS

A high-power solid-state RF amplifier combines the RF power from hundreds of power-amplifier elementary modules in few stages, each equipped with a RF power transistor capable of delivering only a few hundred watts. The last stage is named as amplifier tower. Each power-amplifier elementary module is biased with its own switching power supply or DC converter of voltage a few tens of volts. The ripples of bias voltage contaminate the RF output of RF power transistor. A design of a solid-state RF amplifier combines with *N+n* redundancy of power-amplifier elementary modules is implementable in a direct manner to ensure its extremely high operational reliability, even though the mean time between failures of an individual power amplifier elementary module might not always be great.

A high-power solid-state RF amplifier has become an alternative RF source for RF operation of a storage ring since the successful pioneer development at 352.2 MHz at synchrotron SOLEIL [13]. Thereafter, ESRF selected an *upgraded* version of the SOLEIL-type 352.2-MHz high-power solid-state RF amplifier [14] as part of its machine upgrade programme, and is already in routine operation for booster and storage rings with promising performance [15]. A solid-state RF amplifier with RF power transistors as a product of semiconductor technology will certainly replace an RF source based on vacuum-tube technology, such as a klystron and IOT. Even when it is only a matter of time, the replacement timing is still crucial for decision making, depending on the operational RF frequency and average RF power rating. A 500-MHz high-power solid-state amplifier is the next milestone to pass; considerable effort is dedicated at SLS [16], NSRRC [17] and SOLEIL [18], among other light sources and private companies.

Tracing the path of historical development of a solid-state RF power transistor over 20 years, the features of high gain, high efficiency, high RF power output, and great ruggedness (acceptable for operation under high VSWR) have been pursued to create new records for diverse applications. An RF power transistor configured with a push-pull topology produced with LDMOS (laterally diffused metal-oxide semiconductor) technology is at present commercially available, delivering, at the 1-dB compression point, maximum RF output more than 900 W, CW, at 500 MHz. Considering operation in a CW mode, heat more than 600 W is continuously dissipated on the circuit board of a power-amplifier elementary module, with an average power density up to 230 W/cm^2 dissipated on the RF power transistor. Because the lifetime of semi-conductor products degrades exponentially proportional to its die temperature, the enduring reliability of the components of the amplifier circuit, not only the RF power transistor but also the matching capacitors, output balum etc., is a major concern of design and selection of a high-power solid-state RF amplifier for operation in a storage ring. The thermal requirements become relaxed for its application to booster RF operation because its average operational RF power becomes small. Decreasing the maximum RF output power from an individual power amplifier elementary module of a solid-state RF power amplifier similarly extends its mean time between failures, which increases system complexity and cost, not only the power combination but also the DC power supplies. The extra effort required to maintain hundreds of individual power amplifier elementary modules is also a great concern. Taking the high-power solid-state RF amplifiers operated at synchrotron SOLEIL as an example, the transistors LR301 (maximum RF output of 360 W at 350 MHz) and BLF574XR (maximum RF output of 600 W, CW, at 225 MHz) are operated at 315 W and 350 W, at the 1-dB compression point, at RF frequency 352.2 MHz, respectively [18]; the operational statistics of using transistors LR301 based on accumulated operation more than a few tens of thousands of hours gives an annual rate of failure about 3.5 %; failure is due mainly to thermal fatigue, for example, transistor breakdown or solder damage [19]. Regarding the requirements to maintain individual power-amplifier elementary modules on a regular basis, the mechanical layout of a high-power solid-state RF amplifier must take into account the convenience and efficiency of maintenance which inevitably sacrifice compactness.

A solid-state RF power transistor with great ruggedness is desirable for its application to a light-source RF application because the high-power isolator dedicated for an individual power-amplifier elementary module becomes the most expensive circuit component, apart from its switching power supply. Installing a high-power isolator with a full-power dummy load between an accelerating RF cavity of a storage ring and a solid-state RF amplifier, similar to what has been adopted for the klystron or IOT-based RF transmitter, might greatly simplify the design challenge, providing an alternative to the SOLEIL approach.

The operational cost becomes a great burden on a modern light source because of the substantially increased cost of electric power in recent years. Operating a solid-state RF amplifier at high efficiency makes its application to light sources even more attractive. Considering that the requirement of the maximum operational RF output power for a light source increases with time after its commissioning together with the increased operational beam current and the number of insertion devices in operation, the efficiency of an RF power transistor decreases significantly unless its working point such as bias voltage etc. becomes re-optimized. Retuning the working points of individual RF power transistors ensures highly efficient operation at varied RF output power rating, but also increases system complexity and cost. An improper adjustment might cause low efficiency and a short lifetime of some power-amplifier elementary modules because of a wide spread of optimal working points among individual elementary modules. It is

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worthwhile to design a module circuit insensitive to a performance deviation among individual RF power transistors and other circuit components such as high-power capacitors, handmade layout, etc. To make production of circuit boards applicable to automation is also of importance to reduce the capital cost. Because the high-power solid-state RF amplifier is finally combined with a few amplifier towers, modifying the RF power combined from the amplifier towers with the time to allow a selectable rating of maximum RF output power provides a workable solution to maintain the operation of a solid-state RF amplifier at reasonably great efficiency but with variable rating of maximum RF output without usage of complicated adjustment algorithm.

PERSPECTIVE

The cost of a high-power solid-state RF amplifier might become considerably less than that of a klystron-based RF transmitter in the near future, so enabling the replacement of klystron-based RF transmitters in many light sources, but a klystron will survive in coming decades because of its applicability for a MW power rating.

Production of a high-power solid-state RF amplifier operated at high average power highly reliably is still a considerable challenge. A design depending on working frequency might experience a different outcome. Mastering the details of a power-amplifier elementary module in-house is still essential for highly reliable operation of a solid-state RF amplifier, identically to mastering the knowledge of high-voltage technology for highly reliable operation of a klystron-based RF transmitter.

The development of an RF power transistor has been much more rapid than that of a high-power vacuum tube. The power RF transistor of best performance available on the market will become extinct more rapidly than those vacuum tubes available already in the past decade. Considering the nature of the graceful degradation of solid-state RF power transistors, how to realize a solution for the enduring maintenance of a solid-state RF amplifier on a time scale of 20 years must be carefully considered during the planning phase.

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