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SOLID-STATE HIGH VOLTAGE, DC POWER DISTRIBUTION & CONTROL

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1. ABSTRACT

Future high voltage, high power systems in the early stages of planning include U.S. large accelerator programs such as the Next Linear Collider (NLC), Spallation Neutron Source (SNS), and international systems at DESY, CERN and KEK. There are also many nuclear fusion and multi-megawatt sytems proposed for construction or upgrade. Each of these programs faces the challenge of distributing and controlling the high power required by tens to hundreds of RF amplifier tubes (e.g., klystrons) cost effectively.

In this paper, we present a new approach for distributing and modulating power based upon recent technological developments in high voltage, high power, solid state switching. DTI's development of fast, high voltage, opening and closing solid state switches enable, for the first time at high voltage, a nearly lossless "DC Transformer". With this DC transformer (i.e., down converter or buck regulator), it is now possible to distribute unregulated high voltage DC power in a large facility, and regulate and control it at the klystron. This approach is significantly more compact, less expensive, and more reliable than conventional methods of power distribution.

2. THE OPPORTUNITY

The early 20th century saw the triumph of Westinghouse's AC power distribution scheme over Edison's DC distribution approach because efficient AC power transformers were available, and DC transformers were not.

But, AC distribution is expensive, complex to manufacture and maintain, and inefficient. Typically, only 10% to 20% of the grid power provided to these systems is converted to RF power. The rest is converted to heat, which must then be removed via a complex plant infrastructure.

Recently, high power Insulated Gate Bipolar Transistors (IGBTs), capable of handling hundreds of kilowatts each, have become available. Along with the development of effective methods for combining these devices into very high power circuits, the opportunity for the replacement of traditional AC distribution technology with efficient DC voltage transformers has been created. We will describe this as DC Power Distribution and High Frequency Solid State Power Control.

3. THE ELEMENTS OF DC POWER DISTRIBUTION

The key to the next generation of power distribution and control systems is the availability of a fast, high voltage, solid state, opening and closing switch. Figure 1 shows a DTI PowerMod™ high voltage, solid state switch which operates at 125 kV, 400A, and up to 50 kHz in burst mode. A high voltage pulse from the unit is shown in Figure 3.

Using DTI's high voltage solid state switching technology, the power distribution picture is dramatically simplified. Figure 2 illustrates the concept of transformed three-phase DC power supplied to devices called "switching buck regulators". The route from source to klystron is described as follows:

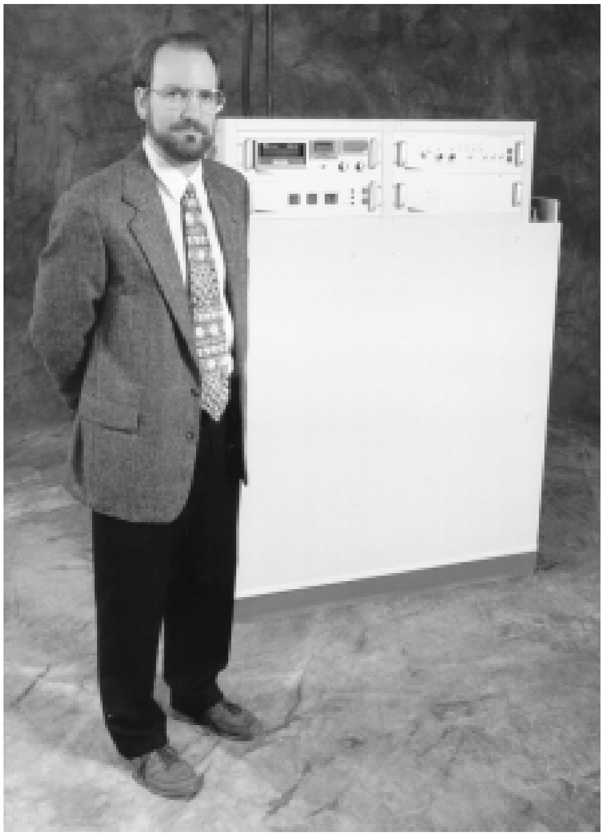

Figure 1: DTI PowerMod™ 125 kV, 400A Solid State Switch with co-author Dr. Jeffrey A. Casey

- Three-phase high voltage power is taken from the power grid in an outdoor switchyard, and routed through SF_6 circuit breakers prior to going to the step-down transformer.
- The step-down transformer is a standard utility outdoor transformer (~ 50 MW). It transforms power from 230 kV AC to approximately 70kV AC (in the 100 kV DC example used here). This 70 kV AC power is then rectified to provide 100+kV unregulated DC power.
- The unregulated, 100+kV DC power is distributed throughout the facility using single pole, outdoor, pole-top

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switchgear and fuses. This equipment replaces the 3-phase 13.8 kVAC switchgear used in the conventional approach, and has the advantage of being simple, inexpensive, and essentially maintenance free.

- Power is routed next to a solid state high voltage switch configured as a ‘switching buck regulator’. The switch is composed of a patented, series stack of high power IGBTs. The IGBT switch is used to Pulse Width Modulate (PWM), or Pulse Frequency Modulate (PFM), this higher, unregulated voltage from the rectifier down to a diode stack and LC filter. The high speed variable PWM/PFM switching serves as the voltage regulator for the system, allowing control of the output voltage over a wide range (5-100kV) at constant power output. If the switching frequency is much higher than the AC frequency (i.e., 5-30 kHz vs. 60 Hz), the PWM can actively compensate for rectifier ripple, as well as provide very fast voltage regulation in pulsed operations.

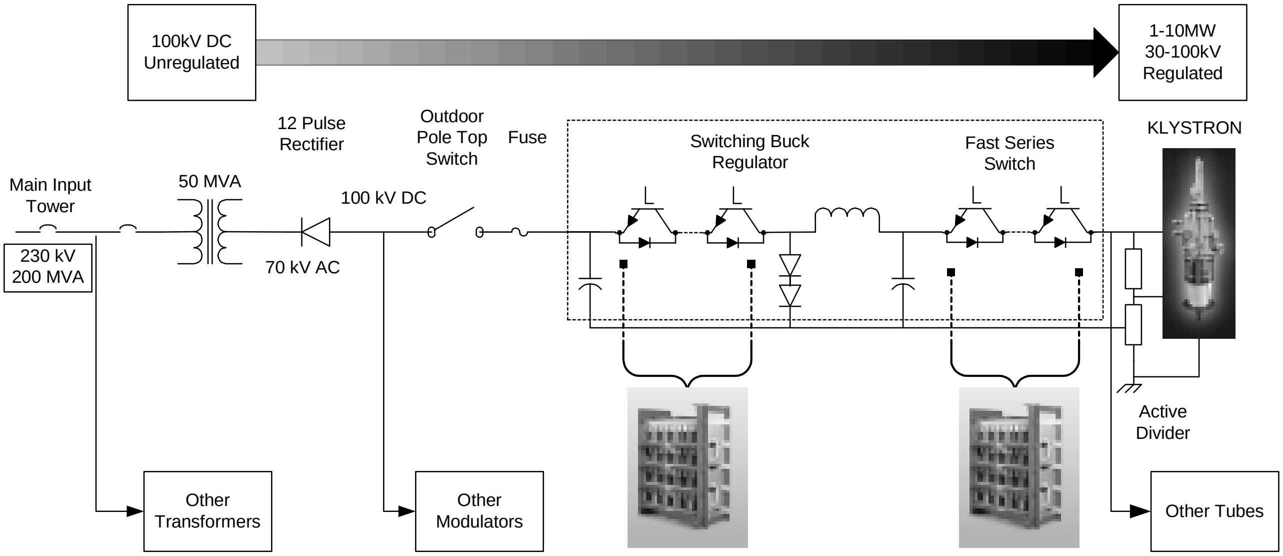

Figure 2: DC Power Distribution Scheme to a Klystron

The only magnetics required in this regulator is the series inductor, an air core assembly measuring approximately one cubic foot. It is inexpensive to build, because it consists of a single layer winding and no metal core.

DTI has conducted a buck regulator demonstration using a commercial DTI 3 MW peak power modulator. Pulses from the demonstration of a few milliseconds show a flat top current trace and confirm the suitability of the switch for this application.

- A second solid state high voltage IGBT switch serves both as a pulse modulator (where needed) and as a fast disconnect in the event of a klystron arc. This switch can detect an arc and open in less than 600 nanoseconds, thereby preventing damage to the klystron much more effectively than a crowbar. For pulsed systems, the speed of the switch allows pulse-to-pulse agility from 1 microsecond to DC, at pulse repetition rates up to and beyond 10 kHz.

The entire buck regulator and series switch combination is essentially composed of two of the solid state modulators as shown in Figure 2. These units, approximately 60 ft^3 each, replace all of the equipment after the initial distribution transformer in the conventional approach.

4. Benefits of DC Distribution and Control

4.1 Simplicity

The DC power distribution and control approach eliminates the large, expensive transformers, series-pass tubes, and 13.8 kV switchgear required in the AC method. Further, DTI’s high voltage switches are both opening and closing switches, eliminating the need for the specialized crowbar protection circuitry.

4.2 Efficiency

DC Distribution and Control eliminates 60 Hz SCR regulators and series-pass tube regulators / switch tubes, improving the efficiency and lowering the cost of power delivery. Primary 60 Hz SCR controllers have a bandwidth intrinsically limited to below the 360 Hz switching speed of the SCRs. On the other hand, a 20 kHz switch has nearly two orders of magnitude higher regulation speed capability. With high speed regulation, the series mod- regulator tube is not necessary, and as much as a 10 kV to 20 kV voltage drop out of 100 kV (200 kW – 400 kW at 2 MW) is no longer wasted. This is an immediate increase of 10%-20% in overall efficiency.

For a 100 kV series switch, the comparable voltage drop is 200V (4 kW, or 0.2%). The efficiency from the overall buck regulator / series switch combination is estimated at over 98%. In a 2 MW CW system, at $.05/kWH, each percent of inefficiency wastes approximately $10,000 per year in electricity costs. Therefore, eliminating the voltage regulation tube alone saves $100K-$200K annually. This cost savings alone may justify the selection of solid state switching power supplies for future high power systems.

Finally, increased efficiency significantly reduces the need for cooling systems to support the power distribution and control system, further minimizing infrastructure and facilities costs.

4.3 Reliability

The conventional AC power distribution architecture offers several "single points of failure". When one of these points fails, the entire power supply chain for a klystron is brought down.

In contrast, the risk of system failure is much lower with DC distribution and control. Each solid state switch consists of a number of IGBTs in series, typically derated by 30% or more. IGBTs, if they fail, fail shorted. This allows continued operation of the switch, even when individual elements fail. Any failed modules need only be replaced during routine periodic maintenance.

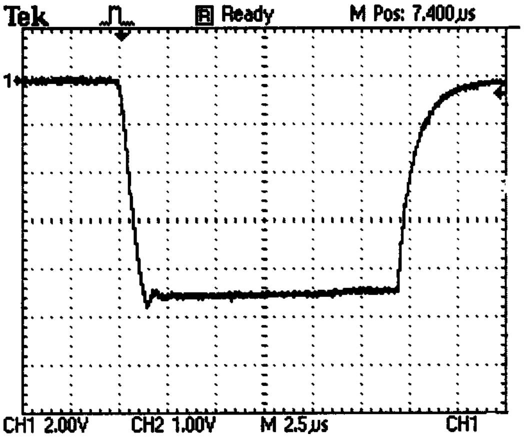

Figure 3: Nearly Ideal Pulse from PowerMod™ 100-150.80kV, 90A into Water Resistor

The modularity of solid state electronics enables this basic design to be delivered in virtually any voltage (up to 200 kV) and current (up to 2000A) combination without significant engineering or modifications to manufacturing processes.

Finally, the use of a second fast series switch brings an unprecedented level of flexibility to pulsed power systems. These switches can provide pulses between 1 microsecond and DC, in response to arbitrary pulse commands. They can also operate at 20 kHz and beyond.

4.4 Cost

The entire switch shown in Figure 1 can be built with commercially available components, and fabricated through conventional assembly techniques. No specialized machinery is required to assemble it, and no complex magnetics are used in construction. Even the largest assemblies can be moved easily with a manual pallet truck.

The largest cost components in this design are the semiconductors (IGBTs). Because of their widespread use in locomotive engines, subway cars, elevators, and a wide range of electrical motor drive and power supply systems, these devices are evolving at a rapid pace, especially in comparison with vacuum switch tubes. In the last decade, we have seen the switching speed and power handling capability of IGBTs increase by an order of magnitude (200 kVA to 4 MVA), at essentially constant prices. **This puts high power electronics, for the first time, on a favorable, long term cost reduction path. This is the equivalent of the computer industry's Moore's Law of continually higher performance per unit cost, but applied to power systems.**

Today, a 100 kV, 2MW buck regulator, with a series switch, can be built for approximately $500k USD. This cost will decline due to increased semiconductor performance and decreased manufacturing costs. In contrast, estimates for the equivalent conventional approach are $2- 3M USD, and show no trend towards cost reduction.

5. CONCLUSIONS

The emergence of high power, solid state electronics enables a new architecture for systems that deliver power to RF tubes such as klystrons- DC power distribution and control. The components to build and operate such a system are available today and have been successfully demonstrated by DTI.

The clear advantages of this architecture will lead to the use of DC distribution and control for future high power RF systems. For those responsible for the design and operation of these systems in the radar, accelerator, and fusion engineering communities, this will mean...

- Lower Capital Acquisition Cost
- Higher Levels of Tube Protection
- Higher Efficiency
- High Reliability
- Lower Lifecycle Cost