A NEW SOLID STATE HIGH POWER PULSED MODULATOR

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Abstract
The CLW modulator represents the first successful application of high-power IGBT switching modules to meeting the requirements of multi-megawatt peak power modulators for microwave amplifier applications. Unlike some other solid-state modulators, no semiconductor switches are placed in series in this system. Neither are the switches connected in parallel. Rather, each switch drives a segment of the pulse transformer core, in a configuration we refer to as a "fractional-turn primary" arrangement. As no PFN is required the width of the output pulse can be adjusted by simply adjusting the trigger duration of the IGBT switches and no PFN ripple occurs on the pulse-top. The volume of the complete modulator is about 10% of a classical unit of the same power. The advantages of this new concept will be discussed with details of a unit that has been in continuous use for more than two years.

1. INTRODUCTION

The firms of Scanditronix Medical AB, D Woodburn & Co. Ltd. and Crewson Engineering, Inc. have jointly developed an all solid-state high power pulsed modulator (US patent no: US5905646) for klystrons, magnetrons and other applications requiring precisely regulated rectangular pulse trains. A concrete example of this "CLW" modulator (named after the inventors, Crewson, Lindholm and Woodburn) is the 140 kV, 95 A, 0 to 300 Hz, 10µS modulator used in the Scanditronix 50MeV MM50 ARTS cancer treatment system. The new modulator uses a number of IGBT switches, operating at relatively low voltage, to replace a high voltage hydrogen thyratron switch. This system is now installed and operating at the Japan National Cancer Center (NCC) in Tokyo, Japan. It has delivered three years of failure-free service, operating almost continuously. No components have been replaced in this modulator system to date.

This system represents the first successful application of high-power IGBT switching modules to meeting the requirements of multi-megawatt peak power modulators for microwave amplifier applications. Unlike some other solid-state modulators, no semiconductor switches are placed in series in this system. Neither are the switches connected in parallel. Rather, each switch drives a segment of the pulse transformer core, in a configuration we refer to as a "fractional-turn primary" arrangement. This concept is a generalization of the older linear-induction accelerator idea, in which a single-turn secondary is driven by N toroidal magnetic "cells" driven by a relatively low voltage which surround the secondary path. This "Linear-Induction" arrangement provides a voltage step-up ratio of N, at the cost of requiring a very large number of cells to yield a ratio in the 150 to 300:1 range. Our electromagnetic circuit combines the step-up advantage of an N2-turn secondary winding with a 1/N1 "fractional turn" primary to yield a conventional-looking pulse transformer with a voltage step-up ratio of N1xN2, that uses only N2 turns on the secondary rather than the full N1xN2 turns. So we can use fewer drive modules than the "Linear Induction" arrangement, yet achieve lower secondary leakage inductance than a single-turn primary arrangement can, and hence obtain a faster rise of secondary voltage than an equivalent single-primary-turn design. The "best of both worlds" is obtained, so to speak.

A second desirable feature of our system is that no PFN structure is used, so the output pulse width can be adjusted by simply adjusting the trigger duration of the IGBT switches. This is a purely electronic adjustment, done at logic-level voltage. Of course, the pulse transformer must be designed to handle the maximum volt-second product of the largest, longest pulse that will be required. Also, no PFN "ripple" occurs on the pulse-top, so no "tuning" of PFN mutual inductances is required to minimize pulse flatness.

We have used a simple passive circuit to compensate for the voltage droop of the modulator capacitors, and this circuit also helps to limit fault currents in the event of a secondary-side short circuit. The modulator we have built for NCC has been subjected to numerous secondary shorts during its development and testing, with no resulting component failures.

We charge the modulator with a series-resonant switch-mode power supply that acts to first order as a "charge pump" or "current source", and which therefore isolates the input powerline very effectively against the pulsed nature of the load. Older resonant-charged circuits tend to cause the input line current to pulsate in step with the modulator output pulses, while the series-resonant supply effectively prevents this.

The modulator replaces several 2-metre high racks of equipment, which were required when the older thyratron-PFN-resonant charger modulator technology was employed. All support subsystems, including the main charging power supply, the filament supply, DC reset supply and the computer interface electronics, are enclosed in the modulator cabinet, which has a total volume less than 0.5 cubic meter. The klystron is mounted directly on the top cover of the modulator. Modulator components are all accessible, and are mounted in plug-in modules on the side walls of the oil tank which holds the pulse transformer and klystron socket.

One present version of the CLW modulator meets the following performance specifications.

- Peak Output Voltage: -140 kV
- Peak Output Current: 95 A
- Repetition Rate: 0 to 300 Hz
- Pulse Flatness: <0.5% peak-to-peak
- Pulse-Pulse Regulation: <0.5% maximum at any repetition rate
- Pulse Width: electronically selectable from 3 to 10 µS (no access to modulator is required to change pulse width)
- Efficiency: Approx. 80 percent, line input to pulse output
- Input power: 400 V, 3 phase, 50/60 Hz, 50 KVA max.
- No high voltage DC power is used. Modulator drive voltage is 900 volts DC, which means that no series connected solid state devices are used; the only high voltage present is at the pulsed output.
- Passed all EMC/EMI tests performed by SEMKO, the Swedish Testing Laboratory.
- Completely Computer-Controlled, using a Windows NT based software interface written by Scanditronix Medical AB.

The operating parameters can be varied widely to meet other performance requirements. CLW technology can be applied to drive klystron, super-klystron or magnetron loads. It is economically competitive with the older thyratron-PFN technology, and when the greatly reduced maintenance and size/weight characteristics of CLW modulator systems are taken into account, the CLW system is seen to be more cost-effective than older technologies. As there are few components that will age with use, the cost of ownership is considerably less than systems using thyratron tubes.

2. FRACTIONAL-TURN PRIMARY CONCEPT

A numerical example is useful in thinking about fractional-turn primaries. Begin with a pulse modulator of the PFN type, and suppose the output pulse is required to be 100 kV at 100 amps, to use round numbers. The load impedance Rs is 100 kV/100 A, or 1000 Ohms. Suppose the primary of the pulse transformer is driven by a PFN charged to 20 kV and switched by a thyratron tube. The transformer primary is then driven by one-half the PFN charging voltage, or 10 kV, and the transformer must supply a voltage step-up ratio of 10:1. Further suppose that the pulse transformer's core is sized to require a 5-turn primary winding to avoid core saturation during the pulse width. The secondary winding must have 50 turns to supply the required voltage step-up ratio. The core thus supports 2kV per turn during the pulse. The primary pulse current is ten times the load current, or 1000 A.

To replace the thyratron switch with lower-voltage solid-state switches, suppose there are available IGBTs that will operate safely at 1000 V and 1000 A; this is simply an example, there are much larger IGBTs on the market. We choose IGBTs rather than thyristors, as IGBTs can be turned off by removing their gate voltage, while thyristors require a pulse-shaping circuit to drive current to zero at the end of the pulse, and so will need a PFN. We suppose that the existing pulse transformer provides a satisfactory pulse risetime, so it would be convenient to keep the same transformer core and secondary structure and simply rework the primary windings. Doing this will not materially affect the pulse rise and fall-times. Also, to make maximum use of the voltage handling capability of the switches, suppose we eliminate the PFN structure and drive the primary from a simple capacitor. Charging this capacitor to 1 kV will then supply a 1 kV pulse to the primary, while we would only have 500 V if a PFN were used. Of course, the capacitor voltage will "droop" somewhat during the pulse, and we will address this point later on. This idea will not work with thyristors; it makes use of the fact that the IGBT switches can be turned off electronically, giving the possibility of changing the pulse width by simply altering the width of the IGBT trigger pulse, which can be done by software without requiring access to the modulator itself.

If we use a single-turn primary winding, the output voltage will be only 50 kV, and the core will be driven at the 1kV per turn level, so we are not using the core effectively and the output pulse voltage is too small. To restore the 100 kV output voltage while keeping the same core structure we could double the secondary turns. But this is a major transformer re-design, and it does not address the issue of driving the core material properly, at 2 kV per turn. Also, doubling the secondary turns will quadruple the secondary-side leakage inductance, and this will seriously slow the pulse risetime.

The output pulse risetime is approximately 2.2Lk/Rs , where Lk is the secondary-side leakage inductance of the pulse transformer. All else being held constant, the secondary-side leakage inductance is proportional to the square of secondary turns. So doubling the secondary turns will cause a factor of four increase in this inductance, and the same factor of four increase in pulse rise and fall-times. This is unacceptable under the "ground rules" of the "thought experiment" we are conducting.

One way of solving this problem is to connect two of the IGBTs in series, and drive the single-turn primary with 2 kV. This kind of solution is employed in some solid-state modulators, where thyristors are connected in series and a PFN structure is used to shape the pulse. We prefer to avoid the problems of connecting switches in series, so we do not adopt this idea. Is there another way to reach the goal?

Yes; if a 1/2-turn primary is used, one can leave the 50-turn secondary unchanged. Since the voltage step-up ratio equals the secondary turns count divided by the primary turns count, this provides a 100:1 voltage step-up ratio, and restores the 100 kV output pulse without affecting the secondary-side leakage inductance. At first glance this may sound impractical, but it is not. Again, as a "thought experiment", consider sawing the transformer core into two identical cores, each one with half the cross-sectional area of the original. Then we drive each of these cores with a single-turn primary, and mount the cores next to each other so the transformer appears mechanically identical to the original design. This is the "fractional-turn" primary concept in its simplest form.

In practice, the "single-turn" primary windings are composed of many single-turn wires arranged adjacent to each other; this keeps stray inductance to a minimum. If we simply drive one of the two "half-cores" with its own independent 1 kV pulse generator, then we have not avoided the problems associated with series-connected solid-state switches. If one of the two core halves is driven slightly later than the other one, the switches connected to this half will be exposed to a factor of two over-voltage and may be damaged. So, to avoid this problem, we "mix" the drives, so that each of the one-kV pulse generators drives some primary turns on EACH of the two core halves. This way, the overvoltage issue is avoided. This point is crucial to the proper application of the concept.

To conclude the example, we now have a 100 kV output pulse at 100 A pulse current, being delivered by a 100:1 pulse transformer. The total primary current of this transformer is then 100 times the load current, or 10 kA. If each IGBT is to operate at 1 kA, we need ten switches. These are connected as described above, with each switch connected to its own capacitor and connected at its output side to several of the single-turn primaries distributed on the two transformer cores. This method of connection helps assure equal current and voltage sharing among the switches, yet does not place the switches directly in parallel or in series with each other.

If this process is extended to the limit, one emerges with a structure similar to the "Induction Linac" , where a single-turn secondary wire is surrounded by N toroidal cores, each driven by its own pulse generator. In the numerical example, if each core is driven by a 1 kV pulse, then 100 cores (N=100) are needed to obtain a 100 kV output pulse. Again, this structure can cause trouble of any of the N pulse switches is triggered late or is turned off earlier than the rest. The "non-driven" core will be subjected to the full voltage of the (N-1) driven cores, and damage to its associated pulse generator can occur. The solution again is to drive several cores with each pulse generator, interleaving the connections so that any one "late" switch will not spoil the result. We have demonstrated this idea in working CLW modulators by removing the trigger pulses from one or more IGBTs without markedly affecting the output pulse shape or causing any damage to the modulator.

A concrete example of this fractional-turn concept is illustrated in Fig.1. This shows a "fractional-turn" pulse transformer with a 1/2-turn primary structure. At first examination, the pulse transformer looks like a "conventional" transformer used in a thyratron-PFN type of modulator. A closer look shows that the magnetic core is built as two identical cores with a small gap between them. Each of the two "half-cores" is itself composed of two identical cores with a still smaller gap between them, but this is a detail of construction and not essential to the half-turn primary structure.

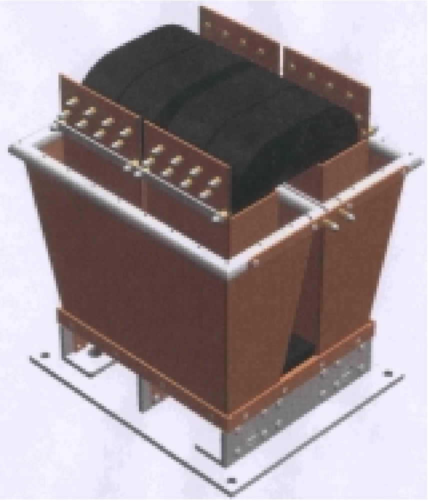

Fig. 1 Pulse transformer with half-turn primary

If the transformer of Fig. 1 is bisected by a vertical plane that passes between the two secondary "baskets", it splits into two identical transformers, with two primaries and two secondaries. The secondaries are connected in parallel at both high and low ends by capacitors, and the two windings serve as a "bifilar" structure to carry power up to the heater of the klystron or magnetron being driven by the negative HV output pulse. This arrangement also leads to very low leakage inductance when compared to a single transformer, and is standard practice in modulator pulse transformer design. Look at the half-transformer on the left (foreground) side of the figure, and one has two cores, each surrounded by its own set of single-turn windings, and with BOTH cores surrounded by the secondary winding. This gives the half-turn primary effect. If each of the two cores is driven by 1 kV pulse generators, a 50-turn secondary winding develops 100 kV pulse voltage.

Note that there are four "core legs" in the overall structure. Each "leg" is driven by its own set of single-turn windings. There are eight of these single turn windings on each "leg". The "low end" of these primaries is connected to a common bus bar, shown running across the width of the transformer structure just below the eight individual "primary high end" connecting screws. There are 32 such individual "high end" primary connection points. In the klystron modulator currently in production, these 32 connections are fed by eight IGBT modules, so each of the four "legs" is driven by two such modules. The eight primary connections are grouped into two sets of four each, with each set driven by a separate IGBT/capacitor module. In this way, we obtain the necessary redundancy of connection to avoid the over-voltage situation described above if one module triggers late or turns off early. The other module still controls the voltage on this "leg" of the core structure in such a case. We are developing a smaller CLW modulator for magnetron drive that uses only four IGBT modules, but again the multiple single-turn primary connections are distributed so each "leg" of the magnetic circuit is driven by at least two modules.

3. PULSE SHAPING

The pulse energy is delivered by switching charged low-inductance capacitors into the primary windings. We use a separate capacitive energy store for each IGBT, and isolate these modules from each other by connecting the capacitors to the DC power supply through diodes. By this means, if a capacitor or IGBT should fail, the energy stored in other modules cannot be discharged through the fault.

During the pulse, the current drawn from the capacitor causes its voltage to decrease linearly. A simple R-L circuit can compensate for this voltage "droop" quite effectively. This principle is illustrated in Fig. 2.

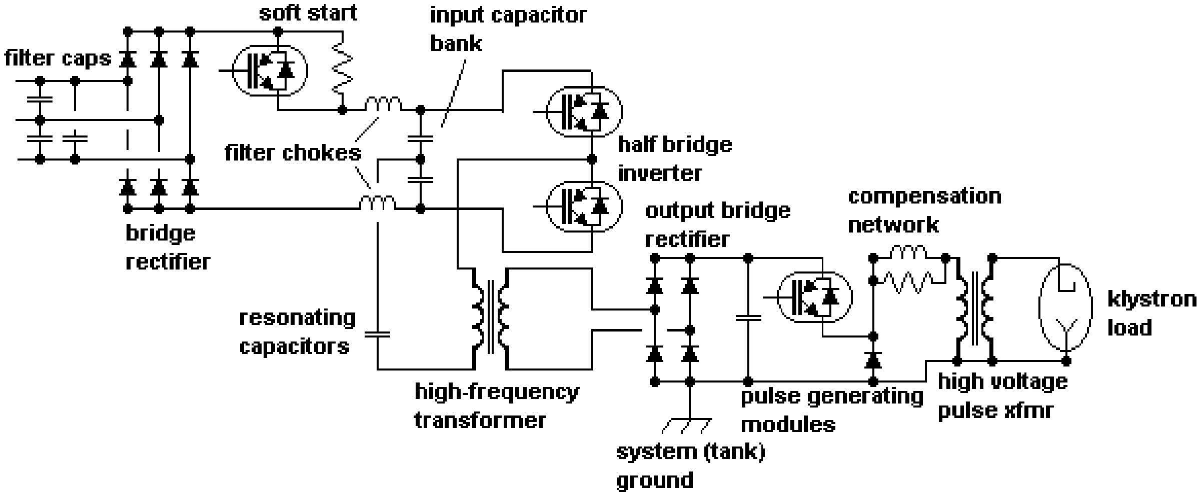

Fig. 2 Schematic Diagram of CLW Modulator

Figure 2 is a simplified schematic diagram of the CLW modulator, showing one of the N pulse generating IGBT modules. The R-L circuit labeled "compensation network" compensates for the droop of capacitor voltage. Each module is connected to the pulse transformer primary through its own compensation network. When the IGBT turns on, the inductor in the compensation network carries no current, and some voltage is dropped across the resistor. As time progresses, the capacitor voltage falls in a linear ramp, as the pulse current is fairly constant during the pulse. While this is happening, the inductor current is increasing. This reduces the voltage that is dropped by the resistor, and the net result is a fairly constant pulse voltage at the pulse transformer primary. This type of pulse compensation results in a power loss of about seven percent for a pulse flatness (peak-to-peak deviation of voltage from a perfectly flat pulse) of one percent. This compensation circuit can be quickly designed and optimized using PSPICE or Microcap.

Another pulse-shaping component is the diode connected from the emitter (output end) of the IGBT and ground. This diode serves two functions: it prevents the emitter voltage from swinging strongly negative and damaging the IGBT when the IGBT turns off, and the small voltage developed across this diode acts to drive down the primary magnetizing current in the pulse transformer, helping reset the transformer core for the next pulse. In practice, we use several high-speed diodes in series at this point in the circuit to develop enough reset voltage; as the pulse duty factor increases, this reset voltage must also increase, as there is less time to drive down the magnetizing current.

Figure 2 also shows the series-resonant IGBT-switched power supply that acts as a constant-current source to recharge the pulse generating capacitors between pulses. This switching supply effectively isolates the pulsed load from the power line, and presents a constant-current load to the power line, which minimizes EMI/EMC problems with the CLW modulator.

4. OUTPUT PULSES FROM CLW MODULATOR

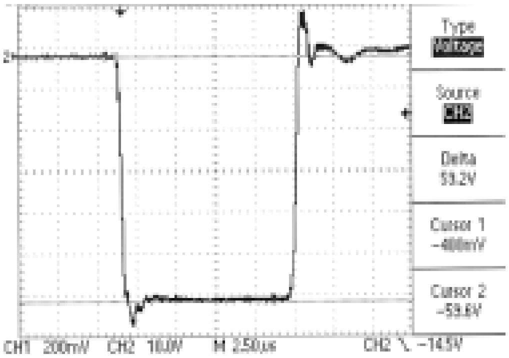

Fig. 3 60-ampere klystron current pulse from CLW modulator

Figure 3 shows a 10-microsecond wide klystron current pulse delivered by a CLW modulator. The slight current overshoot at the beginning of the pulse is charging current drawn by the stray capacitance of the load and pulse transformer terminal, and does not represent electron beam current.

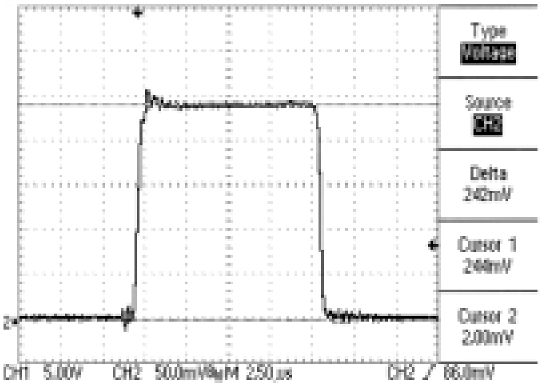

Fig. 4 RF power pulse shape from klystron, 2.4 MW peak

Figure 4 shows the resulting envelope of microwave power delivered by the klystron when the current pulse of Fig. 3 is applied to it. This pulse is flat to better than 0.5% over a 7 microsecond interval, as shown in the more detailed view of Fig. 5.

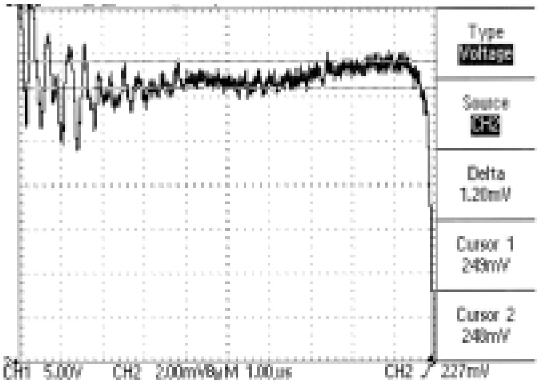

Fig. 5 Detail of the pulse-top of Fig. 4; the cursor lines are separated by 0.49 %

5. CONCLUSION

A new pulse modulator using solid-state IGBT switches has been described. This patented system employs a fractional-turn primary winding on the pulse transformer to obtain very large voltage step-up ratios without sacrificing leakage inductance and hence rise and falltimes. A simple passive R-L circuit is used to flatten the pulse top and compensate for the droop of capacitor voltage, and no PFN structure is needed. Pulse width can be varied by simply changing the width of the trigger pulse applied to the IGBTs. This modulator has proved highly reliable in daily use powering a 50 MeV linac for cancer therapy. It is also being used to power the Scanditronix on-line sterilization system, the Betaline, a 2.5 MeV e-beam system. Further information on this modulator will be provided on request by the authors, and the reader is referred to the referenced U.S. patent for detailed descriptions of the concepts involved in the CLW system.