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Optical Transconductance Varistor – Revolutionizing the Smart Grid

Prepared for:

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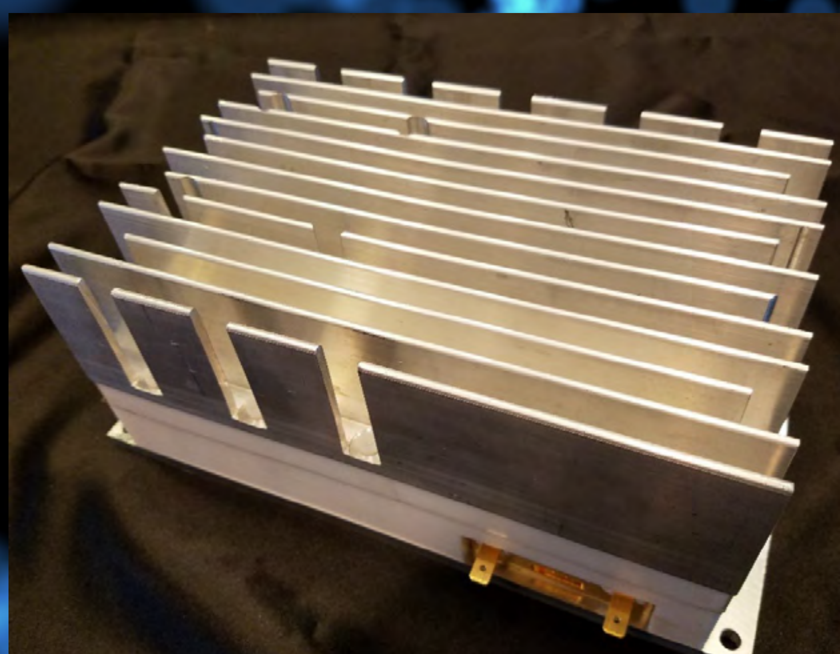
R&D 100
Award Entry



LLNL-TR-823491

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Optical Transconductance Varistor – Revolutionizing the Smart Grid

1. PRODUCT/SERVICES CATEGORIES

A. Title

Optical Transconductance Varistor

B. Product Categories

IT/Electrical: *Electrical Devices (motors, switches, lighting systems, etc.)*

Special Recognition: *Green Tech*

2. R&D 100 PRODUCT/SERVICE DETAILS

A. Primary submitting organization

Opcondys, Inc.

B. Co-developing organizations

Lawrence Livermore National Laboratory

C. Product brand name

Optical Transconductance Varistor

D. Product Introduction

This product was introduced to the market between January 1, 2020 and March 31, 2021.
This product is not subject to regulatory approval.

E. Price in U.S. Dollars

Opcondys products for the smart grid, with high average power requirements, are priced at $9,995, while competitive products in this application space can reach up to $25,000. Opcondys products for use in such applications as air disinfection or medical treatment with pulsed or intermittent operation are priced at $1,050. Prices are anticipated to drop up to 15% when production scales to a higher level.

F. Short description

The Optical Transconductance Varistor (OTV) is a light-triggered semiconductor power switch enabling higher switching speeds than competitors at previously unattainable voltages to facilitate more efficient grid-scale power conversion, reduce expensive, environmentally-damaging energy losses, and generate the voltages required for medical proton therapy or air disinfection.

G. Type of institution represented

Company/Corporation

H. Submitter's relationship to product

Product developer

I. Photos

Attached inline

J. Video

https://youtu.be/93-p9FsHz5E

3. PRODUCT/SERVICE DESCRIPTION

A. What does the product or technology do?

Integrated controls in the smart grid provide greater reliability and efficiency in the nation's complex network of energy generators and energy consumers. Interactive technologies for the smart grid technologies sense and respond to energy demands to manage low (reduced peak) use, integrate renewable energy suppliers, speed power restoration after blackouts, and improve grid security.

However, many smart grid devices, such as transistors used in inverters, breakers, and other equipment to control the electricity delivery, suffer from electrical losses and limited voltage and current. These shortcomings impact grid reliability more and more as the nation adds energy storage capabilities for renewable sources such as solar and wind power.

The Optical Transconductance Varistor (OTV) significantly improves upon existing technologies by maintaining higher output power at higher switching frequencies and shorter pulse widths than is possible with other devices. Shortening the transition from off-to-on and vice versa reduces energy losses to resistive heating for more efficient electricity conversion, with significant economic and environmental benefits. Specifically, the light-controlled OTV **switches over 10 times faster** than today's transistors, **cutting energy losses in half** to **save one billion kilowatt-hours of electricity per year**. If widely adopted on the grid, **the OTV would eliminate 750 million tons of greenhouse gasses annually by 2050.**

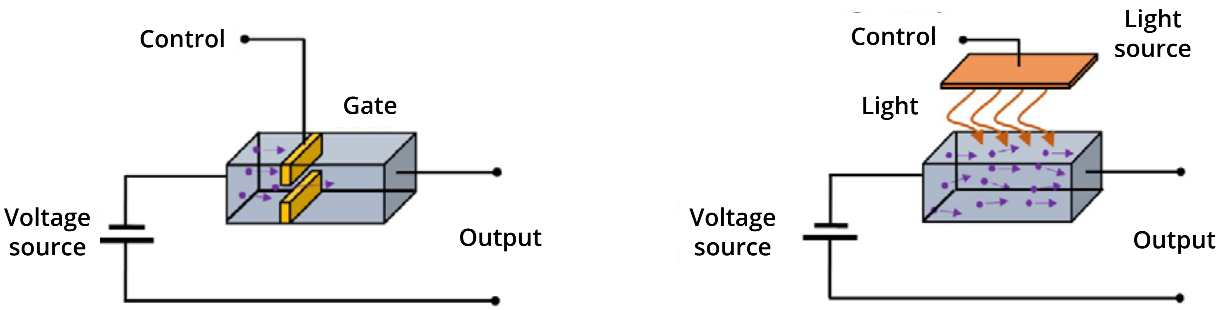


Figure 1: Compared to current smart grid control technologies (left), the optically-controlled OTV (right) switches 10 times faster, reducing energy losses by 50% to save one billion kilowatt-hours of electricity per year.

The OTV can replace high voltage power switching devices used in electric grid modernization including metal-oxide-semiconductor field-effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs), thyristors, and thyratrons, among others. Unlike devices in which the voltage drop through the device occurs across a narrow region at the junction, thus limiting voltage and current, the OTV enables a voltage drop across the bulk of the device, reducing the electric field concentration for greater switching and voltage handling capability. Higher voltage capability means that fewer devices are needed.

The unique OTV design **enables devices to be combined to virtually any voltage and current**, simplifying equipment design. The resulting **reduction in size, weight, and capital cost streamlines the lifetime operating expense of the nation's energy grid** and reduces siting size and acquisition needs for smart grid equipment.

The OTV's straightforward design is **readily manufactured** to reach the marketplace more quickly, further reducing equipment development costs. Lower cost, more energy efficient equipment for the smart grid **increases energy security and reliability in a time when electricity powers more and more of the nation's essential needs**.

Reducing smart grid equipment costs also facilitates **greater adoption of renewable energy sources**. The OTV can be used in converters and breakers for High Voltage Direct Current (HVDC) transmission, the most efficient means of transporting wind and solar energy over the often long distances from where it is generated to where it is needed. In fact, **OTV's reduction in energy losses on a typical 500 megawatt HVDC line would save enough energy to power 10,000 homes**. The OTV can also be used in inverters for grid-tied energy storage systems, which are essential to accommodating intermittent renewable energy sources.

The OTV is a bulk conduction device, easily adapted to any application where a fast, high voltage switch is needed. Therefore, in addition to grid applications, the OTV's faster switching speed enables more compact and lower power devices used in health care. In medical accelerators used in cancer therapy, the OTV switches high voltage to produce x-rays. Inside air disinfection systems, the OTV controls high voltage fields that kill pathogens.

B. How does the product operate?

Existing smart grid controls rely on a semiconductor junction of dissimilar materials that forms a drift region for control. When a control signal is sent to the gate, charge carriers must cross this region before current can flow through the device. The transition time between off-and-on is fundamentally limited by the drift velocity of the carriers and length of the drift region needed to hold off the switched high voltage, leading to significant energy losses during transition. The voltage and current capabilities are also limited by the junction. Often, many devices must be used to operate at grid levels, resulting in bulky, expensive, and potentially unreliable equipment.

Early research leading to the development of the OTV indicated that silicon carbide (SiC), typically a good insulating material, becomes conductive when illuminated with an intense light source. More intense light yields greater conductivity. **At the heart of the patented OTV design is a bulk piece of silicon carbide that, when illuminated by an intense light source, becomes conductive instantaneously, enabling the OTV to switch significantly faster—literally, at the speed of light—and cut energy losses in half.** Thus, the OTV eliminates the semiconductor junction and, instead, relies on photonic properties of wide bandgap materials. The below-band-gap light also enables the bulk conductivity changes which enables very high voltage and power handling.

Specifically, the light-triggered OTV operates by excitation of electrons (or holes) from deep level, vanadium dopants in semi-insulating SiC, a wide band gap semiconductor. When illuminated with an intense light source, such as a laser or light-emitting diode (LED), the switch closes and voltage is delivered to a load. When the light source is removed, the switch rapidly opens due to recombination of the carriers. The laser or LED is integrated in the module and light is delivered directly to the switch by fiber or free-space illumination. Control of the OTV is similar to MOSFET's and IGBT's. A signal from a computer driven controller or signal generator is sent to a driver that provides power to the OTV's light source.

The OTV also responds linearly to input light, giving exquisite control over the conductivity. The device offers an unprecedented combination of voltage hold-off, switching speed, and linearity that cannot be matched by more conventional power electronics.

Most power electronics use silicon, which cannot withstand the same electric fields as SiC. Emerging SiC and gallium nitride (GaN) power electronics will be more efficient than silicon, but, due to inherent trade-offs for all-electronic switching, will never reach the combination of high voltage handling and switching speed of the OTV. The OTV's ability to handle high voltages at high switching speeds reduces electrical losses that are inherent in typical semiconductor devices.

Because of its unique design, OTV is capable of higher power density and switching speeds than competing Si IGBTs and and SiC MOSFETs. Thus, OTV will enable higher efficiency power conversion, a major source of loss in electricity transmission and contributor to CO2 emissions. It also facilitates a low power method of killing airborne pathogens and compact linear induction accelerators for more effective cancer therapy.

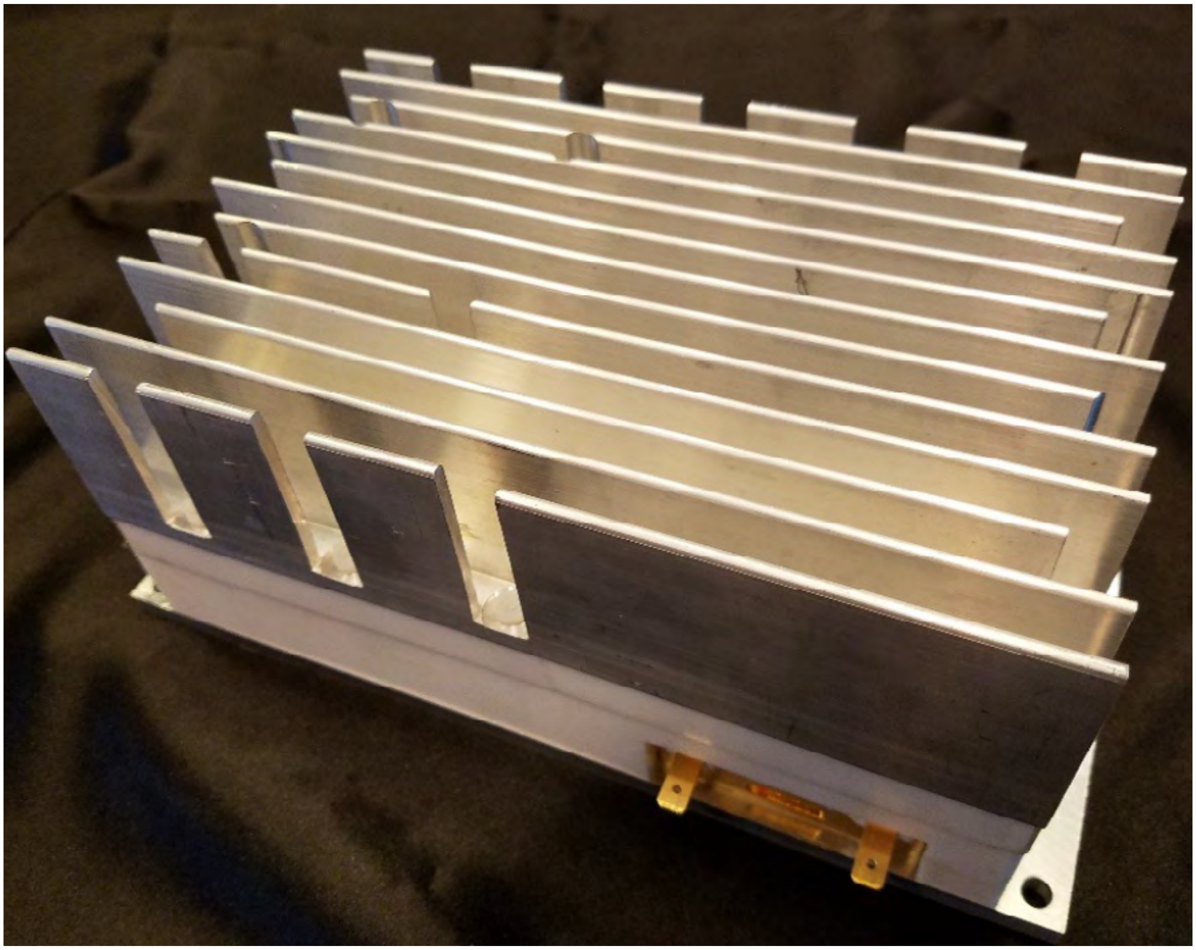


Figure 2: A 20 kV, 10 A OTV module containing the light source, SiC switching material, and heat dissipation fins. The OTV operates similarly to existing IGBT modules but with higher voltage capability and greater energy efficiency.

C. Product Comparison

The OTV offers unprecedented performance compared to conventional IGBTs, thyristors, or power MOSFETs. The key performance advantage of the OTV is improved switching speed at very high voltages. Most power devices trade voltage for switching speed. This results in reduced output power as the switching frequency increases. For example, the outpower power of a 6.6 kV Si IGBT drops by 90% at 10 kHz. A 15 kV SiC-MOSFET sees a similar drop at 25 kHz. The OTV, by contrast, drops only 20% at 125 kHz.

Demonstrated

- **20 kV, 2.5 A operation**
- **Frequency variation to >125 kHz**

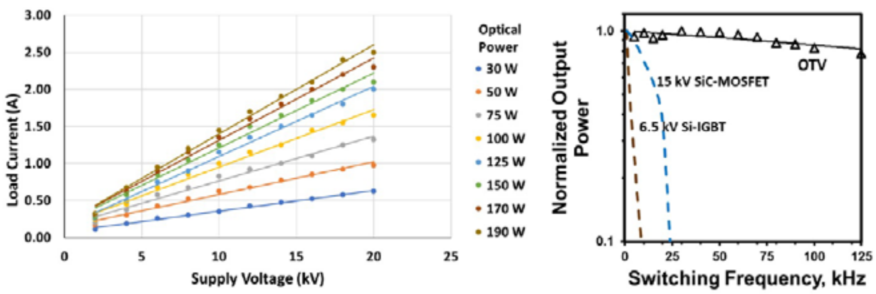
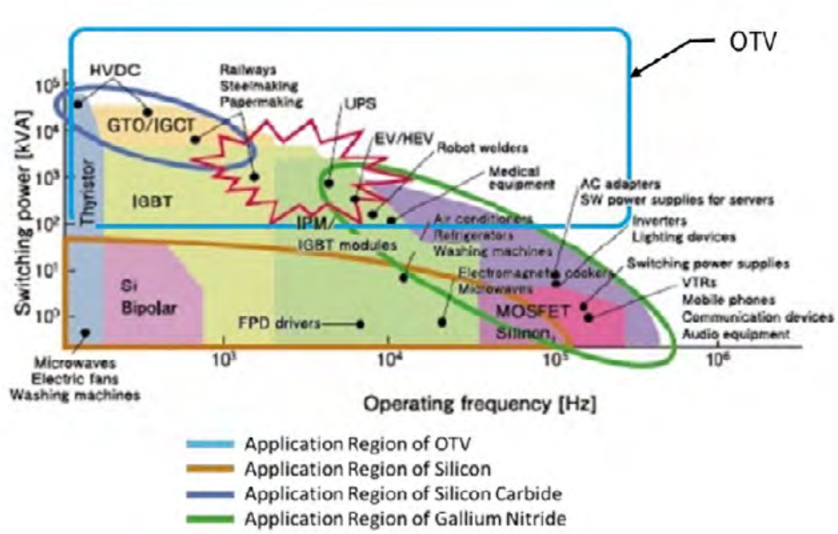


Figure 3: The OTV exhibits a transconductance-like property similar to MOSFET's with linear control of load voltage and current (left). Compared to a SiC MOFSET and Si IGBT, the OTV power output shows dramatically less degradation at higher switching frequencies (right). Bulk conduction means there is no loss of transmitted power at higher operating frequencies.

Figure 4: OTV operates at a higher switching power across all operating frequencies compared to competitive technologies.



Competitors

Parameter	Infineon IGBT Module	Wolfspeed Developmental Module (SiC power MOFSET)	OTV	BENEFIT
Operating Voltage (kV) Operating Current (A)	6.5 kV 500 A	10 kV 15 A	>30 kV >20 A	**Reduces number of devices required, system size, and siting needs**
Switching Time (nanoseconds, ns)	500 ns	200 ns	< 10 ns	**Faster switching reduces energy losses**
Switching Energy Loss (mJ)	4,300 millijoule (mJ)	33 mJ	< 1 mJ	**Reduced energy losses improve efficiency, save electricity costs, and reduce greenhouse gas emissions**
Price per Device Number of Devices Required	$3,400 Multiple	N/A Anticipated to be higher than OTV when commercialized Multiple	$5,000 Single	**Fewer devices required lowers capital costs and siting requirements**
Material	Silicon	Silicon Carbide	Silicon Carbide	**Wide band gap Silicon Carbide can support higher temperatures and higher electric fields than Silicon yielding smaller, more efficient devices**
Electrical isolation enables cascading	No	No	Yes	**Simplification of cascading or paralleling for greater voltage and current capability**
Streamlined, Manufacturing Process	No dozens of high-energy demand processes	No dozens of high-energy demand processes	Yes three-step process	**Faster manufacturing speeds market entry and facilitates faster integration of renewable energy resources**
Non-Toxic Manufacturing	No	No	Yes	**Reducing toxic chemical use is desirable**
Market Entry Investment	High - $100M	High - $100M	Low - $7M	**Lower bar to market entry enables U.S. competitiveness**

Table 1: Comparison of OTV with other smart grid technologies

D. Limitations

The key limitation of the OTV compared to conventional power devices is the requirement of a light source. However, the continued advancements in solid state LEDs and LDs renders this less important.

4. SUMMARY

The Optical Transconductance Varistor (OTV) significantly improves upon current smart grid devices used to control electricity delivery. The OTV maintains higher output power at higher switching frequencies and shorter pulse widths than competitors, therefore shortening the off-to-on transition to cut energy losses in half compared to today's transistors. In fact, it widely adopted, the OTV could save one billion kilowatt-hours of electricity per year and eliminate 750 tons of greenhouse gases annually, by 2050. OTV's unique design enables devices to be combined to virtually any voltage and current, reducing size, weight, and capital cost for smart grid equipment. **With the expansion of the smart grid and introduction of renewable energy supplies, the OTV will be critical in providing the reliability and efficiency to integrate alternative energy, manage energy demands, speed power restoration after blackouts, manage energy, and improve grid security**.

5. CONTACT INFORMATION

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6. AFFIRMATION

By submitting this entry to R&D Magazine you affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product. You affirm that you have read the instructions and entry notes and agree to the rules specified in those sections.

7. REFERENCES

There are no references for this entry.

8. APPENDIX

Letters of Support (separate files):

William Waldron, Advanced Light Source, Lawrence Berkeley National Laboratory

Morgan Maher, McGill University

Publications (separate files):

Sampayan, S.E., Grivickas, P.V., Conway, A.M. et al. Characterization of carrier behavior in photonically excited 6H silicon carbide exhibiting fast, high voltage, bulk transconductance properties. Sci Rep 11, 6859 (2021). https://doi.org/10.1038/s41598-021-85275-6

K. Sampayan and S. Sampayan, "Wide Bandgap Photoconductive Switches Driven by Laser Diodes as a High-Voltage MOSFET Replacement for Bioelectrics and Accelerator Applications," 2019 IEEE Pulsed Power & Plasma Science (PPPS), 2019, pp. 1-4, doi: 10.1109/PPPS34859.2019.9009741.

K. Sampayan and S. Sampayan, "A 20 kV, 125 kHz Photonically Driven Power MOSFET-like Device," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), 2019, pp. 4546-4550, doi: 10.1109/ECCE.2019.8912299.