Factorized Power Accelerates Coral Reef Restoration

According to the latest figures over 70% of the world's coastlines are eroding, with 200 million people worldwide reliant on the protection that coral reefs offer. With 99% of remaining reefs projected to disappear by 2040, communities and livelihoods are at risk in areas such as Mexico, Indonesia and numerous smaller island habitats around the world. CCell uses renewable energy sources such as solar, wind and wave energy to power their reef growing systems. To drive a precisely calculated current through the seawater, Vicor recommended its FPA for efficiently converting wide-range, renewable energy into precision power delivery for the point of load. **Martin Walker, Vicor Business Development Manager, USA; Will Bateman, CEO CCell, UK**

The mission of CCell Renewables (**www.ccell.co.uk**) is to combat coastal erosion and enhance marine ecosystems by restoring damaged coral reefs and growing new ones on a large scale. The technique, invented by Dr. Wolf Hilbertz and based on the electrolysis of seawater, is revolutionary. In just five years it can produce incredibly strong limestone rock that would normally take hundreds of years to form. Where Herbitz grew small restorative reefs, CCell is building much larger structures which are expected to have a far-reaching positive impact on the coastal ecosystem.

Research shows that total wave energy is growing by 0.4 % per year due to rapid warming of our oceans. If reefs could be restored or created and could reduce the energy of waves by 5 – 8 %, it would be possible to revert the impact of waves hitting the shore to levels from nearly 20 years ago. As a result, coastline erosion would be stopped or even reversed.

To achieve this, the limestone structure on which coral grows must be created on a large scale without impurities, with a strong molecular structure and grown at an optimum rate. The electrolysis process must be precise. It cannot be too fast or too slow: too slow and nothing will grow, too fast and the limestone will not be tenable.

Precision and power challenges

The challenges are numerous in growing sustainable reefs on a large scale in remote locations and several hundreds of meters offshore. CCell use renewable energy sources such as solar, wind and wave energy to power the reef-growing systems. Selecting the best approach usually depends on the reef's distance from the shoreline. To effectively combat erosion, ocean waves need to be dissipated around 300 m from the shore.

To grow 360 m^2 of coral reef requires approximately 2 kW of power. While on paper wave energy devices can be expensive when compared to solar panels, the farther offshore the devices are located, the more efficient wave energy converters become. In several projects the converters will be alongside reefs that are over 700 m from the shore. As well as using its system to patch up existing reefs, the company is planning a 300 m long reef with residents that will be only 70 m from the shore. This will be powered partly by solar and partly by the wind.

All of these renewable power sources have one thing in common: their power generation creates a widely varying output voltage due to constantly changing environmental conditions.

The primary power source

The CCell primary power generator is based around an innovative wave-energy converter that uses a sturdy paddle to drive a hydraulic system for producing electricity. This power source delivers a wide-range and varying voltage created by the wave energy that must then be regulated precisely to grow tenable coral. As well as having to manage a highly variable source voltage, the electrolysis process is governed by the seawater

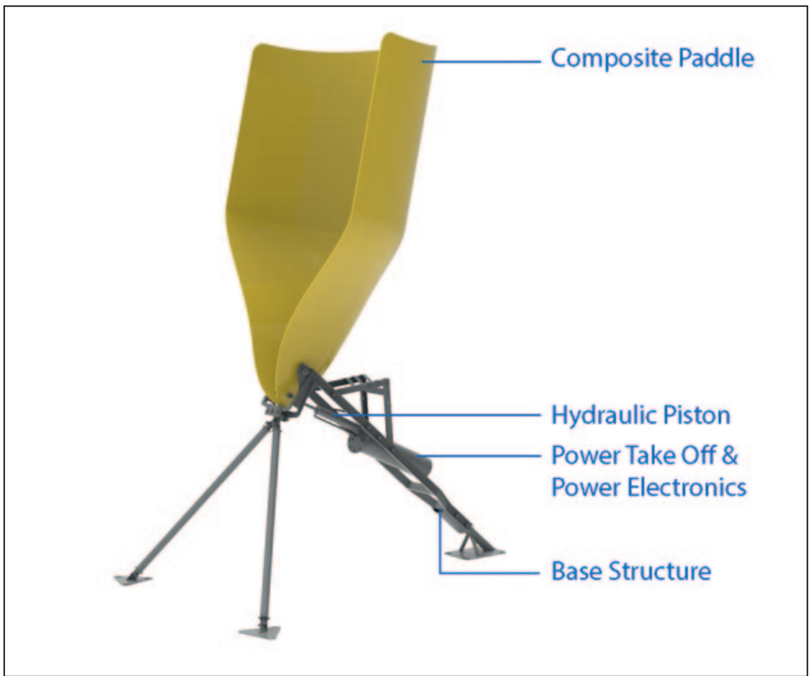
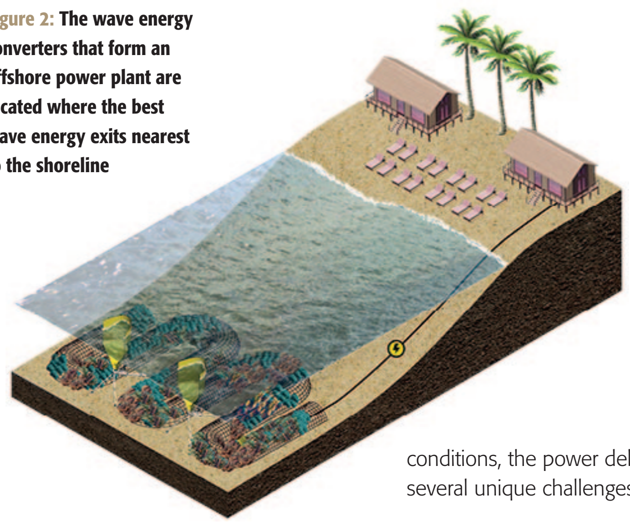


Figure 1: **Primary power generator is based around an innovative wave-energy converter that uses a sturdy paddle to drive a hydraulic system for producing electricity**

Figure 2: The wave energy converters that form an offshore power plant are located where the best wave energy exits nearest to the shoreline



composition, water temperature and flow rate over the electrodes (anode and cathode) formed by the steel frame. All of these variables have to be closely monitored, measured and controlled to ensure that the potential difference between the anodes and cathodes drives a precisely calculated current through the seawater between the electrodes. This is necessary to achieve the optimum electrolysis process to grow strong, sustainable limestone (calcium carbonate) deposits from minerals found in the sea water.

Growth is managed precisely by controlling this potential difference (electric field) between the electrodes within a 'goldilocks zone,' which for the Ccell system is between 1.2 and 4 V, depending on all the environmental conditions mentioned previously.

The power delivery network

To grow 360 m^2 of coral reef requires approximately 2 kW of power. The wave energy converters that form an offshore power plant are located where the best wave energy exits nearest to the shoreline. The output voltage of the wave converters can vary between 35 and 70 V.

The power delivery network (PDN) consists of a front-end conversion and regulation stage followed by a downstream point-of-load (PoL) regulation stage for the systems monitoring and control electronics. Power is delivered via a long cable to the electrolysis system which is placed very close to the steel frame located on the ocean floor where the reef will be rebuilt or created.

With a power level of 2 kW and a goldilocks zone of 1.2 – 4 V for the potential difference between electrodes, the electrolysis power system must be capable of delivering up to 1,666 A at the lower end of the voltage range. With these conditions, the power delivery network has several unique challenges:

- Conversion and regulation of a wide 36 – 70V input voltage for the control system onshore and the electrolysis system out on the reef;
- delivering high power (2kW) to the offshore electrolysis system up to 700m offshore;
- delivering high current (up to approx. 1700 amps) and maintaining voltage regulation at a controlled level. The voltage range is 1.2 – 4V between the steel cage electrodes, and system needs to be able to change voltage and current delivery rapidly under ever-changing conditions.

Vicor recommended its proven Factorized Power Architecture (FPA), confident that it would meet all of the power delivery needs and also achieve high current density to minimize the power system size deployed in the ocean. The FPA incorporates a current multiplier which also has a fast transient response.

The FPA solution

Advanced processors are now requiring higher currents as their load voltages drop below 1 V.

Density and low noise at the point of load are becoming even more critical to processor performance. The continuing challenge for system designers is to accommodate lower voltages with faster transient response and better power system efficiency in an ever-shrinking board area.

Factorized Power Architecture solves these problems – it takes the DC/DC converter functions of regulation and conversion and factorizes it into its two constituent parts. This allows for complete optimization of each function, a high efficiency regulator coupled with a high density currentdelivery device for various low voltage high current loads. FPA consists of a Pre-Regulator Module (PRM) and a Voltage Transformation Module (VTM)/Current Multiplier. These two devices work in partnership with one another, each fulfilling its specialized role efficiently to add up to the complete DC/DC conversion function.

The PRM supplies a regulated output voltage, or 'factorized bus' from an unregulated input source.

This bus feeds one or more VTMs which transform the factorized bus voltage to the level needed by their load, while providing isolation as well. So, a PRM VTM chip set provides the full, regulated, isolated DC/DC converter function. Factorized Power means more space at the point(s) of load, one-half the power dissipation and the regulation function can be remotely located.

Thus the Factorized Power Architecture does what it says, which is to factorize the DC/DC function into two separate modules, a PRM regulator and a VTM current multiplier.

The PRM uses a patented Zero-Voltage Switching (ZVS) buck-boost regulator control architecture to give high-efficiency step-up and step-down voltage regulation and soft start; maximum efficiency is achieved when $V_{IN} = V_{OUT}$, with 99.3 % peak being achieved with the latest PRMs (Figure 3).

The VTM current multiplier (Figure 4) is

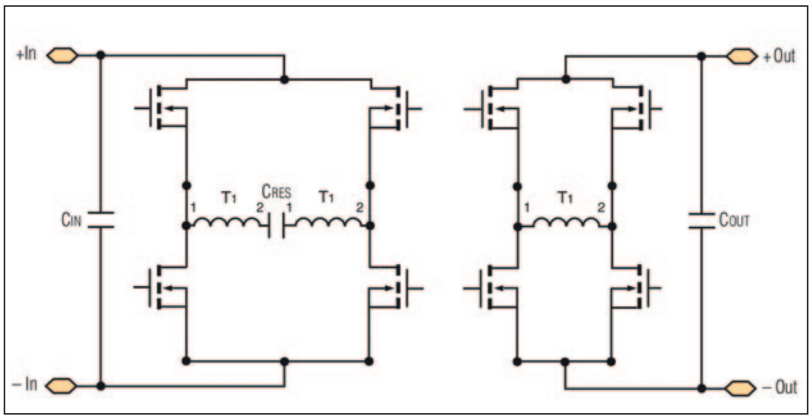


Figure 3: Simplified schematic of the Pre-Regulator Module

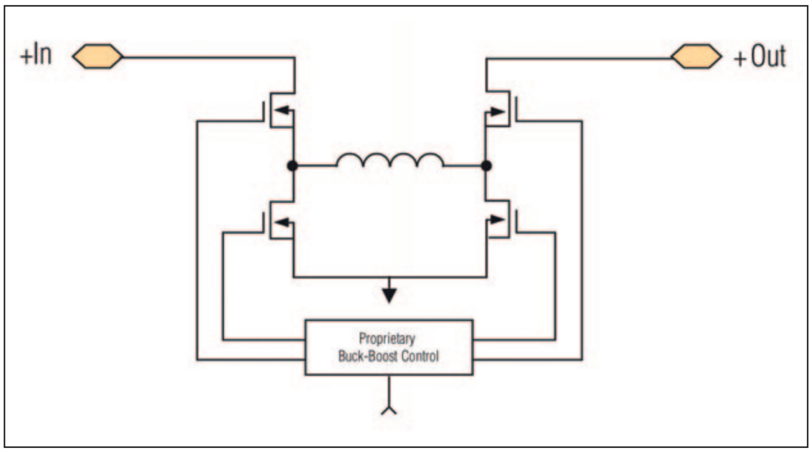


Figure 4: Simplified schematic of the Sine Amplitude Converter

a high-efficiency voltage transformation module using a proprietary Zero-Current Switching / Zero-Voltage Switching (ZCS / ZVS) Sine Amplitude

Converter (SACTM). It operates on a pure sinusoidal waveform with high spectral purity and common-mode symmetry. These characteristics mean that it does not generate the harmonic content that the typical PWM type conversion has and generates virtually minimal noise. The control architecture locks the operating frequency to the powertrain resonant frequency, allowing up to 97 % efficiency and minimizing output impedance by effectively cancelling reactive components. This very low, non-inductive output impedance allows it to respond almost instantaneously to step changes in the load current.

The VTM responds to load changes regardless of magnitude in less than one microsecond with an effective switching frequency of 3.5 MHz. The VTM's high bandwidth obsoletes the need for large point-of-load capacitance. Even without any external output capacitors, the output of a VTM exhibits a limited voltage perturbation in response to a sudden power surge. A minimal amount of external bypass capacitance (in the form of low ESR/ESL ceramic capacitors) is sufficient to eliminate any transient voltage overshoot.

The architecture and topologies of each device are perfect for solving the CCell power delivery challenges.

First, the PRM buck-boost regulator is capable of operating over a wide input voltage range. Due to its ZVS topology, it has very high efficiency and power density and is easily paralleled to deliver higher power. The power delivery to the reef is so far offshore it requires almost 2 kW, but the higher voltage allows reduced cable size and a cost saving. The PRM not only operates over a wide input voltage range but is optimized for delivering higher regulated voltages for the downstream VTM.

The VTM's transformation ratio is called the K factor. The VTM operates like a DC/DC transformer such that if the K factor was 1:8, the output would be 1/8th of the input and the current multiplication from input to output would be 8. The two modules work seamlessly together with the PRM handling the tightly regulated voltage required for the reef, and the VTM handling the conversion and current delivery to the electrodes. For the CCell application the following power delivery decisions were made.

Taking into account the measured voltage drops in the power cables to the reef, the PRM (Figure 5) would regulate the 36 – 70 V input from the wave energy converter to deliver between 9.6 and 32 V on the input of the VTM modules, which have K factors of 1:8, to provide a 1.2 – 4 V output. As environmental conditions are constantly changing, the PRM is regulating the input to the VTM to maintain the desired output voltage.

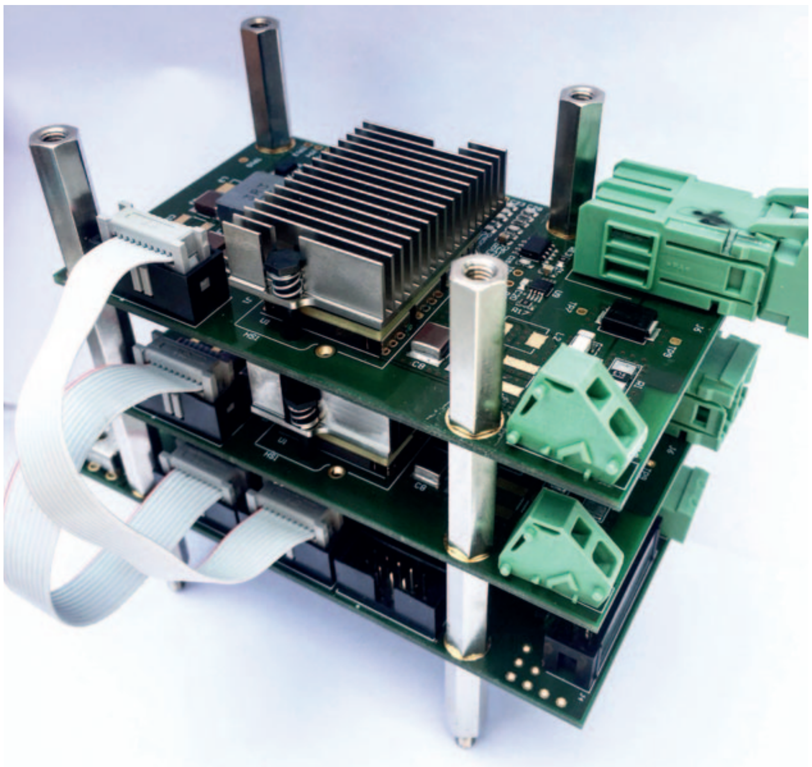


Figure 5: The PRM regulates the 36 – 70 V input from the wave energy converter to deliver between 9.6 and 32 V input of the VTM modules