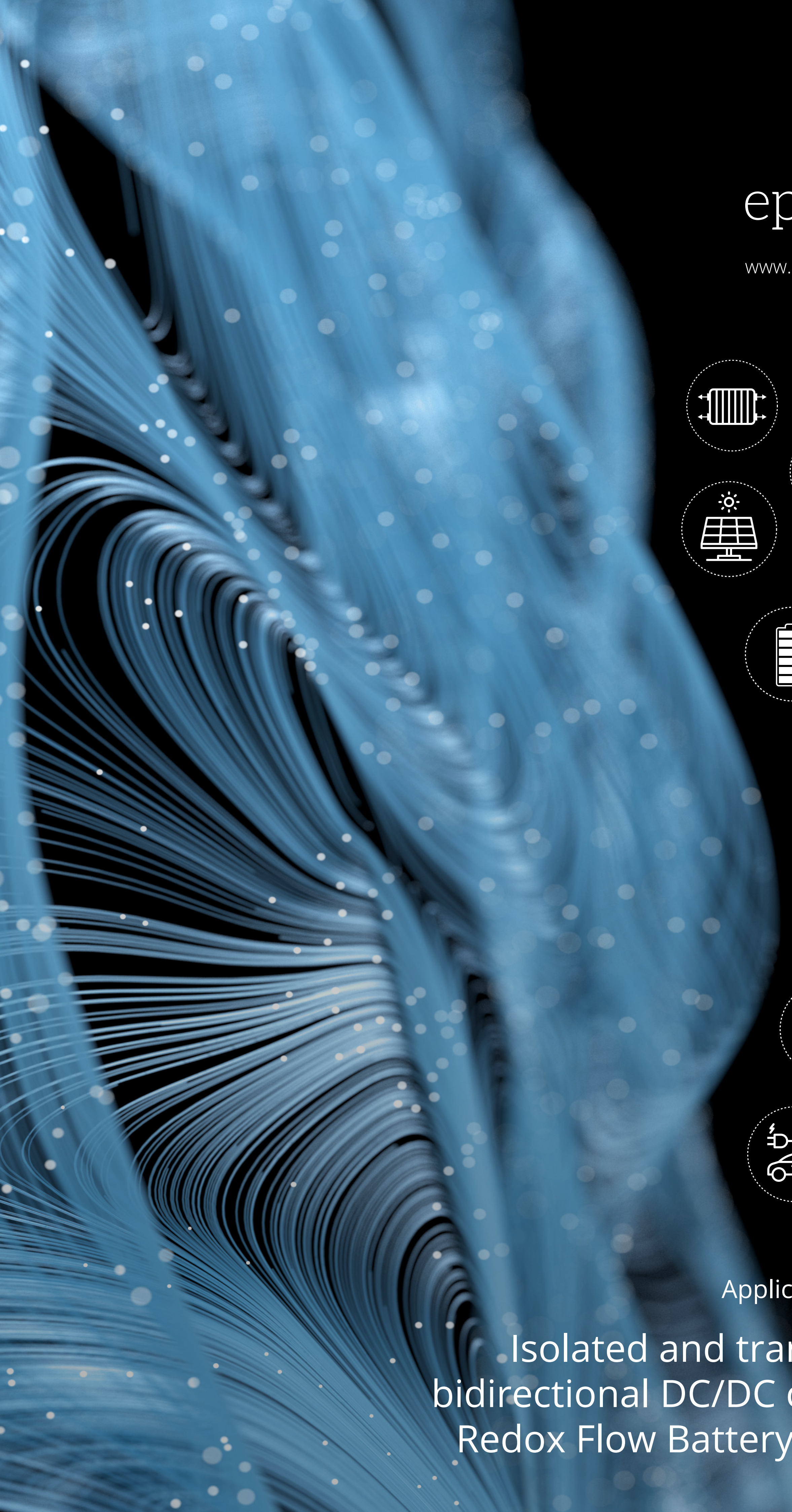

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Application Note - AN061

Isolated and transformerless bidirectional DC/DC converters in Redox Flow Battery applications

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AN061
Isolated and transformerless Bidirectional DC/DC converters in RFB applications

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Isolated and transformerless bidirectional DC/DC converters in Redox Flow Battery applications

The energy transition from fossil fuels to renewable energies is the main driver for the development and implementation of new high-energy density energy storages. Redox Flow Batteries are playing an important role now and will be in the future.

With the increase of renewable sources such as solar and wind, the shape of the net load (net load = total electric demand minus wind and solar generation) has been changing in the last few years.

Such grids would benefit greatly from the use of a battery capable of shifting the load to flatten the net load curve. RFB batteries are optimally dimensioned for an operation of between 3 and 9 hours as the power and energy are uncoupled with the energy cost much lower than the power cost.

In Image: 1, a containerized vanadium redox flow battery capable of handling 50 kW of power. The battery is used to absorb the solar production during the day and shift that energy to the load in the facilities when required. EPIC POWER's bidirectional DC/DC converters are used to regulate the charge and discharge current of each one of the stacks in the container.

Image: 1 – CSIC containerized 50 kW – 100 kWh Vanadium Flow battery with EPIC POWER bidirectional DC/DC converters

Bidirectional DC/DC converters for RFB stacks

RFB stacks are built with several cells stacked in series. Although the standard voltage per cell is around 1.5 V/cell, depending on the electrolyte used, the voltage in each one of the stack cells will differ slightly. Below, the Table 1 shows the most common RFB electrolyte combinations.

Table 1: Voltage and power density per cell.

Electrochemical elements	Max voltage per cell (V)	Power Density (W/m2)
Iron – Iron	1.8	< 1,200
Zinc – Bromine	1.85	~1,200
Vanadium – Vanadium	1.60	~1,000
Iron – Chromium	1.2	< 600

As the voltage per cell is too low to be practical, several cells must be stacked to build a usable battery. Standard numbers normally range between 20 and 50 cells per stack although there are projects in development that aim to achieve the construction of > 80-100 cells per stack.

Increasing the number of cells in series reduces the overall efficiency due to the shunt currents that appear from the differences in the cells along the stack. There is a compromise between the mechanical and efficiency limits of cell serialization in the construction of the stack.

To match the low-voltage levels in the stacks and the high-voltage levels of operation of industrial inverters on the market, Flow battery manufactures follow one of the following paths.

1. Use of low-voltage high-current bidirectional DC/DC converters that connect directly with individual stacks. → Maximizes the efficiency of the system but slightly increases costs. The piping is simple and safety is guaranteed as the energy source is at low-voltage.

   Due to the large voltage difference between the stack side and the high-voltage DC bus, **isolated bidirectional DC/DC converters are recommended**.

2. Serialization of stacks to increase the voltage of operation. → Reduces the cost of electronics but also reduces the final efficiency of the system. The piping to connect several stacks in series becomes more complex.

   As the voltage ratio between the string of stacks in series and the DC bus is minimized, **transformerless bidirectional DC converters are recommended.**

High-current isolated Bidirectional DC/DC converters

Isolated DC/DC converters include a galvanically isolated high-frequency internal transformer. This high-frequency transformer provides the following benefits:

- Galvanic Isolation between the two DC buses avoids the effects of shunt currents that reduce the efficiency of the stacks. It also increases the electrical safety of each stack as it is completely uncoupled from the rest of the elements in the system.
- False detection of faults in the system are avoided, as impedance to ground in renewable solar plants is generally very low.
- A tranformer that adapts voltages provides flexibility to select the ideal switching devices for the low and high voltage side. For example, in applications with a high voltage gap, the switching devices used in each side are different.
- Efficiency (> 96 %) is maintained even with a large voltage difference due to the high frequency of operation.

In Figure 1, a general block diagram of an isolated bidirectional DC/DC converter from EPIC POWER is shown.

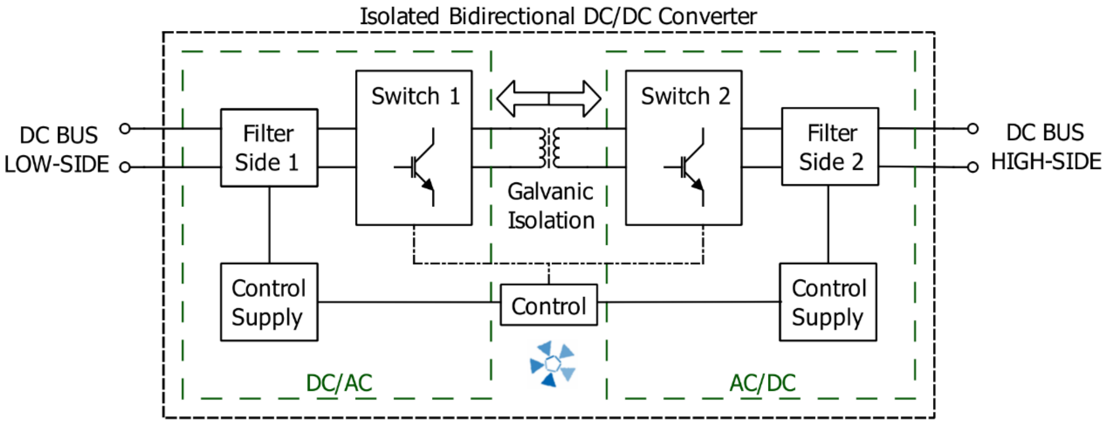

Figure 1: Block diagram of an isolated DC/DC converter

As the most common RFB stack has a voltage < 100 V, the switching devices used on the low-voltage side of the DC converter (block represented as Switch 1 in Figure 1) are commonly mosfets. Mosfet technology has evolved dramatically in recent decades offering the best current density at voltages below 150 Vdc.

Several stacks are normally used with DC/DC converters in parallel to connect to industrial inverters operating at 750-950 Vdc. As the voltage of operation on the secondary side is much larger than on the primary side, the type of switching devices change. To provide a high-power density at voltages > 600 Vdc, silicon carbide transistors have proved to be the best.

In terms of efficiency, most of the losses are found in the switching devices and in the magnetics. As isolated DC/DC converters allow the designer to work with the ideal switching device (Mosfets for low-voltage and high-currents and silicon carbide transistors for high-voltage and low-current) and the magnetics can operate at hundreds of kHz to reduce the losses, the overall efficiency of this type of converters is generally very high.

In Figure 2, we can see an example of efficiency of an isolated DC/DC converter depending on the voltage of operation on each side. As the range of operation is very wide on both sides, there are points at which the efficiency is maximized.

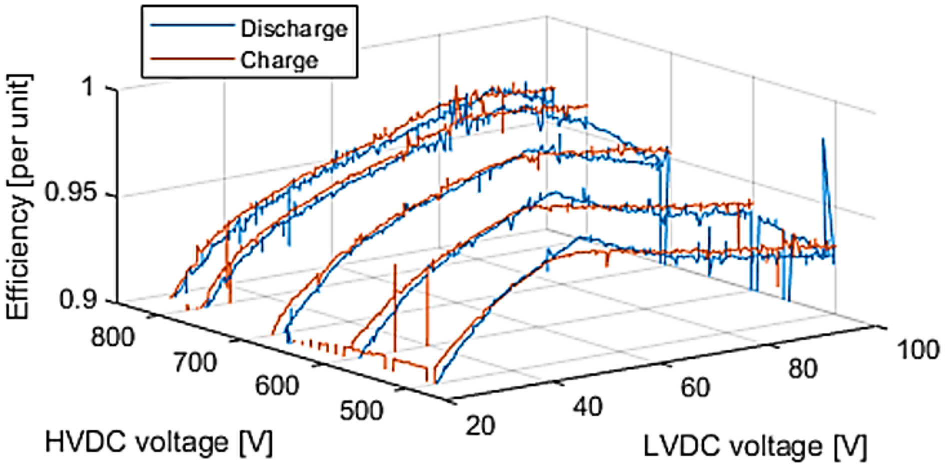

Figure 2. Efficiency map for isolated bidirectional DC/DC converter

The graph, from Figure 2, can be provided for every converter supplied by EPIC POWER. Knowing the efficiency of each point of operation allows the system integrator to optimize the overall system efficiency by choosing the best high-voltage side of operation.

Isolated converters can be parallelized on one side, for example on the DC bus, and completely separated on the other side of operation as depicted in Figure 3.

As EPIC POWER DC/DC converters can integrate the "Voltage Droop" control to regulate the High-side DC bus, the current is evenly distributed among the stacks.

Due to the isolation, if there is fault to ground in one of the stacks, the system can continue running as the insulation to ground of the DC bus is not compromised.

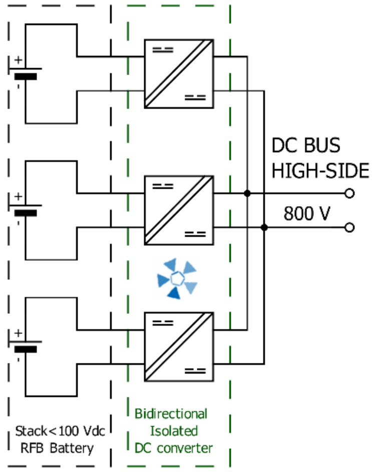

Figure 3: Isolated DC converters in parallel on one side

Isolated bidirectional DC/DC converters are the safest and most efficient option when serialization of stacks is not considered.

High-Voltage transformerless Bidirectional DC/DC converters

Non-isolated or transformerless DC/DC converters share the negative point of connection between the low- and high-voltage side. Because of this configuration, the low- and high-voltage side are not isolated.

In Figure 4, a general block diagram of a transformerless bidirectional DC/DC converter from EPIC POWER is shown.

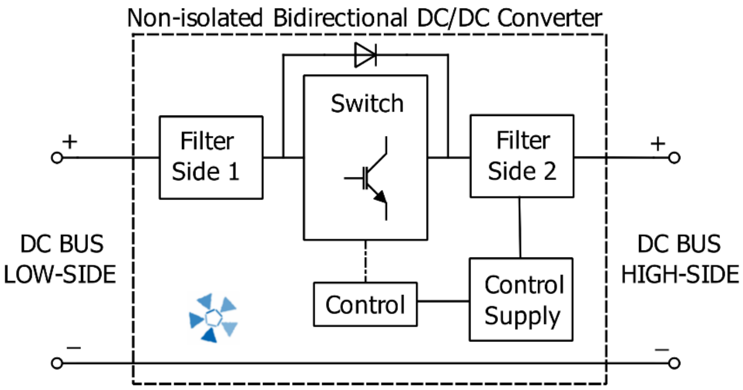

Figure 4: Block diagram of a transformer-less DC/DC converter

Serialization of RFB stacks can reduce the efficiency of the energy transfer and add complexity to the piping distribution but as the voltage of operation is increased, the power electronics required can reduce in cost. This trade-off must be studied in each case to identify if the challenges of safety, efficiency and complexity can be compensated for by the reduction in the cost of the electronics.

Transformerless DC/DC converters only have one switching block, which can slightly increase the efficiency of power transfer if the ratio between the low side and the high side does not exceed 1:4. In those conditions, the switching devices are used properly, and the losses vs power output are optimized.

It is important to reiterate that the lack of galvanic isolation between the low and the high-voltage side requires special consideration at system level to avoid major problems with faults in and out of the system. As most electrolytes nowadays are conductive, any formation of electrolyte outside the stack can eventually create a path to ground that triggers a fault.

In Figure 5 a general diagram showing the effect of the (1) installation impedance to ground (which can be low in large installations), the fault to ground of one stack (2) and the short circuit created between them by another stack (3).

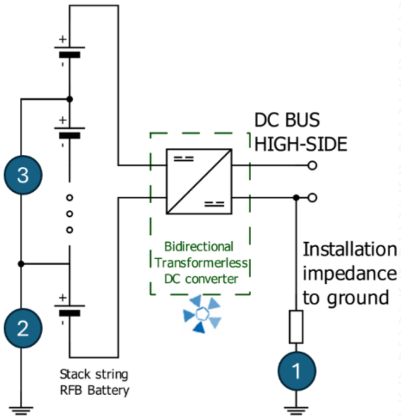

Figure 5: Potential ground insulation faults

In Figure 6, we can see an example of efficiency of an EPIC POWER transformerless DC/DC converter, depending on the voltage of operation on each side.

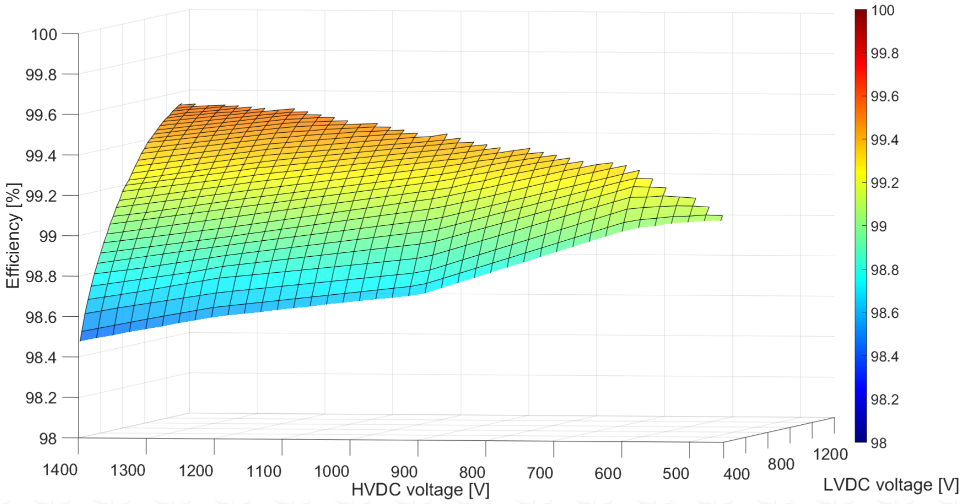

Figure 6: Efficiency map for transformerless DC/DC converter from EPIC POWER

The efficiency is almost flat (between 98.5 and 99.5 %) when the voltage on the low-voltage side reaches values higher than 700 Vdc. Due to the low impact of losses, EPIC POWER converters can be designed with fan cooling and still require a small footprint in the power electronics panel of the system. Below, two general examples of use for a transformerless DC/DC converter are shown:

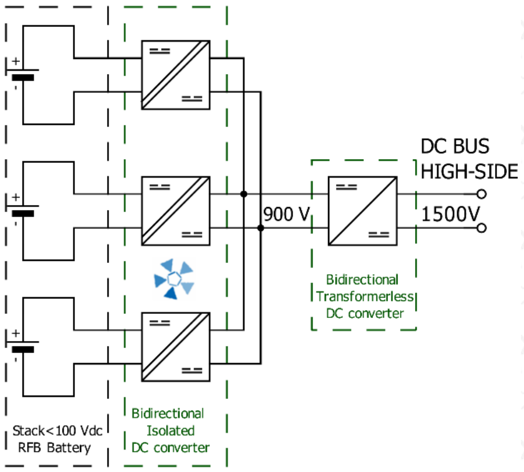

Figure 7: Isolated DC converter per RFB stack + Transformerless converterfor voltage adaptation

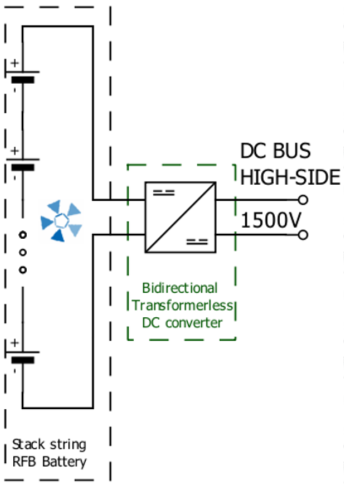

Figure 8: Transformerless DC converter with RFB stack in series

In Figure 7 the transformerless DC converter adapts the output voltage of an isolated DC converter to reach voltages of up to 1500 Vdc.

In Figure 8, with the RFB stacks serialized to form a high-voltage battery string, the transformerless DC converter can adapt the output voltage to meet the requirements of the application.

System regulation – Voltage Droop control

The “Voltage Droop” control is used in DC systems, particularly in distributed generation and microgrids, to allow multiple power sources to share the load efficiently without the need for communication between them. It is based on the relationship between voltage and current.

A “droop” curve is established, which relates the output voltage of a power source to the current it supplies. As the current increases, the output voltage decreases according to a predefined slope. This way, power is adjusted automatically according to this curve. This method ensures that the load is shared evenly among the sources.

“Voltage Droop” control has three key advantages: simplicity (no communication is required between power sources), stability (allowing automatic load sharing), and flexibility (can adapt to changes in load and the number of power sources connected to the system).

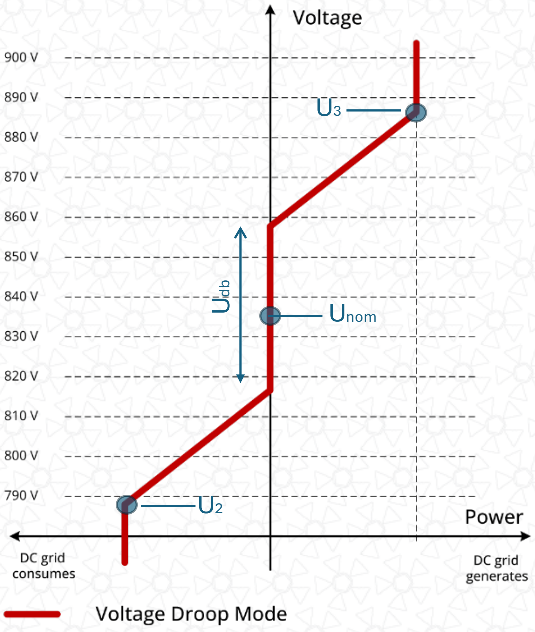

Figure 9: Example of a “Droop Control” configuration

To configure the “Voltage Droop” control, the integrator must only select the following parameters shown in Figure 9. This definition follows CurrentOS standards:

- U_{nom}: Nominal voltage of the application or middle voltage point of the deadband.
- U_{db}: Deadband range in voltage. The converters will not transfer power in any direction as the voltage is not providing information for the converters to operate.
- U_2: Voltage at which the converters will be transferring full power discharging the energy source towards the DC bus they are regulating. If the voltage has reached that point, the DC bus is demanding full power.
- U_3: Voltage at which the converters will be transferring full power, discharging the DC bus they are regulating towards the energy sink.

RFBatteries that include several stacks with DC converters can be configured easily, simultaneously ensuring the even distribution of current across all of them.

EPIC POWER Technology

The bidirectional DC/DC converters developed by EPIC POWER have certain features and certifications that can be useful when working with redox flow battery solutions.

- **Black-start operation**: when redox flow batteries are installed without access to the electricity network, the integrator must offer a way to start-up the system. As the electrolyte would be idle and discharged, the stacks cannot be used as a battery to power-up the system (pumps, inverter, DC converters and others) and an external battery should be used. Generally, a standard lead-acid battery at 24 or 48 Vdc is connected to one EPIC POWER's converter to create a high-voltage DC bus. EPIC POWER converters supply their control directly from a 24 or 48 V battery and can perform a pre-configured start-up sequence to power the system.

- **Pre-charge the RFB stack from 0 V**: when the electrolyte has not been used for a while or it is fully discharged, the voltage at the terminals of the stacks can be very low. DC converters are required to pre-charge the stacks with a limited current until the electrolyte begins to operate within nominal levels. EPIC POWER's DC converters can perform the operation if the voltage on the high side is higher than 400 Vdc. This functionality combined with the black start operation allows up an RFB installation to operate and start- in any condition.

- **Avoid derating at high temperature**: EPIC POWER DC converters are designed to work in harsh temperature and humidity conditions. All the electronic boards and components are coated to avoid oxidation and corrosion from external agents while allowing them to operate at high temperatures. The most critical components in every DC converter are monitored so derating is applied with ambient temperatures higher than 50 ºC.

- **Certifications:** to ensure that integrators can work easily anywhere in the world, several standards for safety, emissions and electrical immunity are considered. Compliance to these standards allows EPIC POWER to certify its DC/DC converters in Europe with CE, in the USA with UL and in Canada with CSA.