FUTURE LOCAL INTELLIGENT TRANSACTIONAL ENERGY NODE FOR EV CHARGING AND MOBILITY HUB

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ABSTRACT

Within the context of EV growing market, this white paper introduces a solution made up of 3-port converter in the 50kW power range to efficiently deliver the energy to fast EV charging terminals (EVSE – Electric Vehicle Supply Equipment). Based on self-supporting hardware, this 3-port bidirectional converter has an AC delta-wired port switchable to a double DC port supporting two PV strings with MPPT (or similar renewable sources). The two other ports galvanically isolated are preferably connected to storage(s) and DC load(s) which is an EVSE for fast charging in this case. Therefore, energy flows from renewable, power grid and local storages are routed at high power rates to supply the EV in an efficient and fast manner, whatever the local AC grid enables. Several practical use cases for mobility hubs are presented based on a local AC-microgrid supporting a cluster of EV chargers connected on a single Point of Common Coupling (PCC) with limited capacity. Moreover, the use cases are supplemented with a no-break capability for highly dependable loads.

INTRODUCTION

Since EV take-off, many companies developed and provided power converters that make possible the energy management for EV charging [EVC] whereas other technologies have yet to be involved to meet decarbonization challenges. After going through a usual case with several 2-ports converters combined to support fast EVSE, this white paper highlights various benefits of the Stabiliti^{TM}, 3-ports bidirectional converters [3-PBC] to manage local renewables, storages and augment the PCC capability to deliver enough energy to the fast EVSE in a timely manner. Such 3-PBC can be operated in two software defined configurations: on a first one, it works as an AC//DC/DC converter & on a second one, as a DC/DC//DC/DC, meaning one of the ports can be switched from AC//DC to DC//DC and vice versa while being fully bi-directional. Another type of 3-PBC with AC/DC/AC topology, named Hercules^{TM}, can be combined with the Stabiliti^{TM} to support additional features. The second section presents the characteristics of these two 3-PBC. The last section shows PROS & CONS like flexibility and efficiency gains under different conditions as well as how better charging time can be achieved. The combination of several 3-PBC working concurrently can be re-purposed to cope with changing weather conditions, multiple AC grid status and actual states of charge [SoC] of the local storages. A smart power flow throughout the microgrid optimizes the use of local energy resources while making the EV charging process more cost effective. This section also describes applications leveraging the Hercules 3-PBC originally designed for backup.

USUAL CHARGING STATION TOPOLOGY WITH SEVERAL 2-PORTS CONVERTERS

It is interesting to have a look on commonly used fast EV charger's setup where well-proven equipment's and technologies are assembled to quickly respond to market demand.

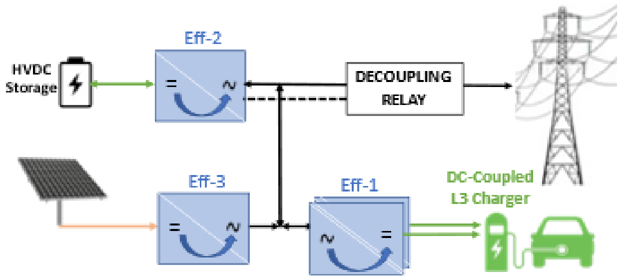

Figure 1. Diagram of a usual charging stations with 3 kinds of two-port converters.

Figure 1 depicts a typical topology of charging station based on three different kinds of 2-ports converters: unidirectional DC/AC for PV's, inverter-charger for storage and galvanically isolated unidirectional AC//DC for EVC's. Indeed, simply add two complementary converters to the existing PV system brings few advantages. But when the grid shuts down, no more energy is exchanged and the EV charging is interrupted. An additional AC islanding relay located at the grid feeder fixes the issue, the inverter-charger switches to grid forming mode driving the two others still in grid following. EV's are galvanically isolated with respect to chassis for safety purpose (IT earth connexion) and the charger embedded into the EVSE must have such isolation too. Typical values of efficiency for different 30kW converter types have been listed for benchmarking although the efficiency levels are subject to variations.

Figures of Peak Efficiency for Converter Types having a nominal power in the range 30..50kW	
Eff-1 / Isolated Unidir. Rectifier	AC//DC = 97 %
Eff-2 / Non Isolated Bidir. Invert/Rectif	AC/DC = 97,5%
Eff-3 / Non Isolated Unidir. Inverter	DC/AC = 98%

Table 1. Relative values of efficiencies used for comparison depending on the kind of converter.

Evaluating the energy conversion paths for all use cases, leads to Table 2 showing poor energy transfer efficiency when the High Voltage Direct Current [HVDC] storage is involved.

Battery-2-EVC	**= Eff-2 * Eff-1**	**= 94,5%**
Grid-2-EVC	= Eff-1	= 97%
PV-2-EVC	= Eff-1* Eff-3	= 95.5%
PV-2-Battery	= Eff-3 * Eff2	= 96%
Average Efficiency Figure of Merit		**= 95,5%**
PV-2-Batt-2-EVC		**= 90.5%**

Table 2. Results of efficiencies obtained for the usual case based on three kinds of 2-port converters.

Assuming a public EV charging station case with multiple EVSE, where the charging time shall be as short as 20 min for 50% or 40 min for 80% recharge, the Battery-2-EVC efficiency is obviously an important criterion because the level of losses decreases the local HVDC storage capability and ultimately the number of vehicles that can be served. For the private companies with multiple EVSE, the charging time can be increased by managing priorities but the efficiency of conversions from grid and renewable sources impacts the complete setup payback too, especially if the charging process shall occur during high tariff periods. Among all results for the "usual" approach, it is shown that the best result stands for the Grid-2-EVC path that can be used while the AC grid is available whereas renewable source and battery management contribute in a poorly efficient way. This also appears to be contradictory with the societal goal of decarbonization that can only be achieved through decentralization of power generations.

THREE-PORT CONVERTERS TOPOLOGY

Two different 3-bidirectional-ports converters [3-BPC] are introduced hereafter. They combine three ports working with AC or DC power sources. This section focuses on specific features of an AC//DC/DC integrated converter named "Stabiliti™" and another AC/DC/AC hot-plug module named "Hercules™" where "AC" stands for 3-phase bidirectional embedded converter and DC for bidirectional embedded converter available through a "port". These two 3-PBC types can be paralleled to scale up the system size. At first, Hercules™, the AC/DC/AC, was launched to back up critical 3 x 230Vac AC loads. Hercules™ output is supported by either the grid through a full double conversion mechanism or the storage as well as any ratio of both. Systems of several hundredth of kW can be designed by paralleling several 3-BPC units. Thanks to full bidirectionality, any energy produced in excess on the load side can be absorbed by the converter and recycled toward the grid or the storage. That's why, lately, they have also been used as energy router for microgrid applications with renewable energy sources leveraging that unique feature of continuous control on the 3 ports ruled by the energy sum always equal to 0. As it comes to Stabiliti™, the AC port of its AC//DC/DC system can drive a 30kW AC tri-phase load while taking a variable 20kW power from PVs on DC port in MPPT mode and 10 kW on the second DC port connected to the battery, configured in NET-0 mode to compensate the PV power and supply the difference to 30kW load and, if the load goes down to 10kW the power in excess from PV dynamically charge the battery.

STABILITI: A configurable 3-BPC

… of which the AC port can be re-configured in DC ports too upon software trigger. The AC port mentioned as AC1 can be turned into a 2 DC ports called DC1A & DC1B sharing a common 0V point. The Stabiliti™ can operate as a 3-port $[AC1]^3//[DC2/DC3]^3$ or as a 4-port: $[DC1A/DC1B]^3//[DC2/DC3]^3$.

The power exponent on squared brackets refers to the number of wires for the associated ports on both sides of isolating barrier. Figure 2 helps understand which port can switch from AC to DC.

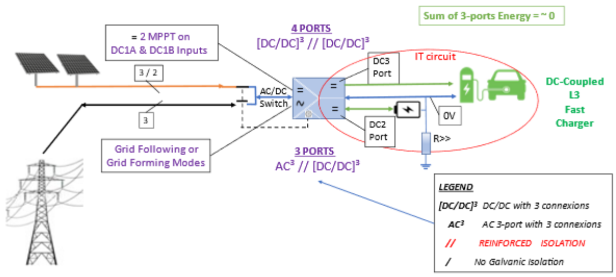

Figure 2. Diagram of the STABILITI™ which is basically a 3-PBC with an AC port that can be turned into a 4-PBC with AC lines used as DC inputs.

The symbols "//" & "/" mean respectively "galvanically isolated" & "non-isolated" ports. The AC1 is a 3 phase delta lines port while [DC2/DC3] describes a double DC port without galvanic isolation between DC2 and DC3 sharing a 0V third terminal (Vdc2-0V-Vdc3). When AC1 is configurated as AC source, it can run either in grid-following or in grid-forming mode and stay bidirectional in both cases. Relying on the isolation between AC1 or DC1A/DC1B ports and the DC3/DC2 ports, the HVDC storage and the EVC can be connected on the same side. With the battery and the EV on the same side, the EVC is advantageously poured from the battery with high efficiency.

Use of the AC//DC/DC mode

The 3-BPC is mainly operated in AC mode and with the AC1 port connected to the grid, DC2 to a battery and DC3 connected to the fast EV charging station. Such configuration aims to charge EV directly from the battery with support from the grid for optimal charging rate required by the EV. The AC1 port nominal rating is 30kW@480V. It can be used at 400V in Europe and other

similar countries with a derated power 25kW to keep up with the port current limit at $44A_{ac}$.
For the DC port, DC2 and DC3, the maximum voltage is $1050V_{dc}$ and the maximum current $60A_{dc}$ leading to a 60kW maximum power exchange between the two ports. Both ports can be used as MPPT, constant voltage, constant current or constant power source. They are operated in either BUS mode when paralleling several converters in voltage sources (multiple connections on same bus) or NET-0 mode, which must be assigned to at least one of the ports to balance the energy sum on the three ports. Voltages around $800V_{DC}$ are consistent with market requirements for fast EVSE and related storages giving approximately 50kW (considering linear derating) available per single Stabiliti™ converter for charging. The next table displays the power capacity versus voltage & max current of the DC port.

MAX DC CURRENT 60A	
POWER (KW)	**Voltage (v_{dc})**
60	1000
50	840
45	750
30	500
24	400
12	200

Table 3. Maximum power rating on DC side versus working voltage.

Description of the [DC/DC]//[DC/DC] mode

Renewable energy sources are expected to grow in pursuance of governments decarbonization objectives. Multiple scenarios are possible including large solar farms (or wind turbines) as part of decentralized microgrid. Due to the nature of the technology some distances can exist between the generation field and the actual utilization spot. In some instances, microgrids can even replace transport lines. For that particular use switching the Stabiliti™ AC port to DC to be operated as HVDC bus while keeping the isolation barrier with DC2 and DC3 ports makes good sense. How does it work?
On diagram of Figure 3, as soon as PV production is high enough for the local PMS (Power Management System), the AC/DC switch is set to DC position, connecting one or two PV strings to the port, starting to work in DC mode and then charging the batteries, the EV or both together when possible. When switched to DC mode, the current limit changes and reaches a maximum of 50 A_{dc} on DC1A and DC1B, leading to a 50kW power transfer through that port at $1kV_{dc}$ on PV side or, alternatively, 2x25 kW when the two ports have +/-$500V_{dc}$ – 0V voltage. Concurrently the PV strings can be connected to DC3 while disconnecting the EVSE if no EV is present so that the solar is not curtailed and stay collected. The energy could even be recycled to the grid in case the battery is full. It is also possible to charge the battery in constant current mode and inject the energy surplus into the grid.
For specific site situations the Stabiliti™ can be paired with Hercules™ the second 3-BPC as introduced hereafter.

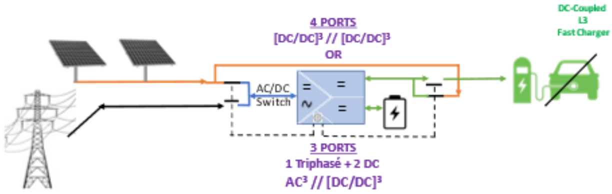

Figure 3. STABILITI™ with the second switch allowing power injection into the grid when there is no EV charging.

HERCULES™: 2nd kind of Multiple port converter

This Hercules™ converter has two AC ports, a DC port and is represented as "AC/DC/AC" where each port will be referred to as "AC1/DC2/AC3". There is no galvanic isolation and even though this technology has been initially developed to secure critical loads, it has also evolved to energy routing with full bidirectionality on the three ports. A schematic for this three-port converter is displayed on Figure 4.

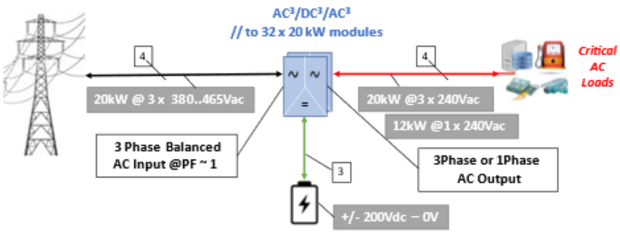

Figure 4. Diagram of HERCULES™ with ratings.

The Hercules module usually runs in three-phase mode on AC1 & AC3 although it may also be configured in single phase on AC3 port. One of its key features is to have a balanced 3-phase input current on AC1 regardless of the actual phase balance of the load connected to AC3. In order to get the 20kW nominal power at the inputs, voltage should range between 380 and 465Vac line-line while a power derating occurs below $380V_{ac}$. Regarding the loads, the output can be set at 400 or $415V_{ac}$ line-line. This power rating stands for a single converter, but they can be parallelized up to 32 modules in stack to reach 640kW nominal power system with a 150% overload for 15s, 130% for 30s or 110% for 60s on a 2 min duty cycle. One recent growing application is called *Power Booster* and is based on the Hercules™ used as energy router for load with higher peak power than the available nominal power source. A typical example involves a 120kW crane on a "weak" PCC or a genset rated for 40kVA… working with six Hercules™ modules in parallel and a battery string at +/-205Vdc-0V able to withstand pulsed current close to $300A_{dc}$. The stack of Hercules™ withstands the peak power demand until the load is softly returned the main

source thanks to continuous power control between 0 and 100%, and reversely. The power on the AC1 source is capped and maintained at the maximum allowable level (in this example ~35kW) while supplying the actual load demand (in this example: 120kW) with the support of the storage (85kW). This *Power Booster* application is like the EV charging process at the mobility hub. It spreads to civil works wherever machineries are now converted to electric.
A brief analysis of energy transfer in the hub during the EVC process leads to the three following conditions to guarantee a continuous energy feeding of a time-dependent load like EVC. The first one comes with a necessary condition on the minimum source power with respect to the EVC:

$$P_{GH} \geq P_{EVC} * DC_{EV} / \eta_{CD} \quad [1]$$

where:
P_{GH} is the maximum power of the AC Grid Hub
P_{EVC} is the EVC average power over all charging times
DC_{EV} is the Duty Cycle of an EVC also expressed in [3]
η_C & η_D are the charging & discharging efficiencies with $\eta_{CD} = \eta_C * \eta_D = \eta_C^2 \sim \eta_D^2$

E_S is the minimum energy in the EVC hub storages:

$$E_S = (P_{GH} - P_{EVC}) * T_{EVC} / \eta_D \quad [2]$$

with
T_{EVC} the statistical average of all EV charging times
T_{HES} the hub energy storage from 0..100% charging time.
This time T_{HES} to charge the hub storage E_S can be used by the hub EMS[Energy Management System] to schedule the EVC requests in a waiting queue, recording the energy stored during each EVC to balance the SoC of the hub storage Energy Es:

$$T_{HES} \geq Es / P_{GH} / \eta_C \quad [3]$$

with
$T_{HES} >> T_{EVC}$ and $DC_{EV} = T_{EVC} / (T_{EVC}+T_{HES})$
$DC_{EV} \sim T_{EVC} / T_{HES}$
The P_{GH} / P_{EVC} ratio for an EVC hub could increase in a close future to more than five with the growing EV number having more and more autonomy and the limit of AC grid nominal power on a hub.
It means that the trend of mobility hub is the renewable energy increasing with maximization of self-consumption.

THREE-PORT CONVERTERS USE CASES

The AC1//DC2/DC3 or DC1A/DC1B//DC2/DC3 converter implements energy management in the mobility hub with help of a local Power Management System [PMS] integrating all necessary site information's like EVC terminal status and total energy storage with SoC. The DC3 ports supplies the EV terminals as soon as the isolation-to-earth/chassis check is ok and payments information related to the ready-to-charge car are known. The charging current level related to the EV battery SoC is then set. As Table 3 shows it, a wide range of working voltages is possible for the Stabiliti™ converter so that many different EV types can be operated equally through the 3-BPCs systems, minimizing recharging time while maximizing the use of possibly available renewable sources.
The two following use cases integrate either one or two types of 3-BPC by pointing out advantages & drawbacks for each solution. Before illustrating those cases, keep in mind that the focus of this white paper are EV fast chargers: DC-coupled Level 3 and AC-coupled Level 2, each EVC terminal type being obviously supplied in a different way.

EVC with Stabiliti 3-BPC and AC-µGrid

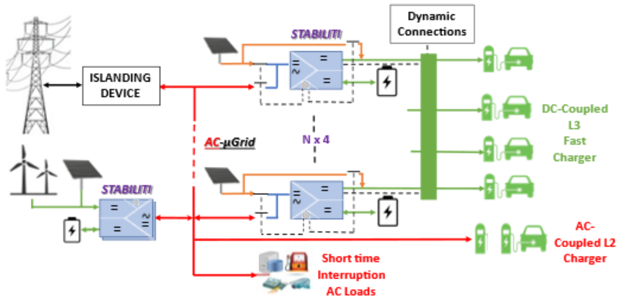

Figure 5. Diagram of a charging station made up of AC chargers and DC Fast chargers.

Figure 5 illustrates a charging station that could take place in a shopping centre. This site configuration is only based on Stabiliti™ converter and flexibility for all EV types rises when setting them up by groups of four units to offer a wider range of charging capabilities (See table 5).

NB OF CARS CHARGING	EV VOLTAGE (V)	CHARGING POWER FLEXIBILITY PER EV (KW)
4	4 x 400	24
2	2 x 400	48
4	4 x 600	36
2	2 x 600	72
4	4 x 800	48
2	2 x 800	96
1	1000	220

Table 5. Possible power rates depending on the number of EV charging and their voltage.

Table 5 illustrates how energy flows from a cluster of four converter units for several EV charging voltages. The flexibility and modularity of the Stabiliti™ make easier the implementation of several groups of four Stabiliti ™ units to get high power capabilities regardless of power limitations at the PCC. A four Stabiliti ™ system works with 3 interconnecting power contactors wired between the four DC3 ports: a first contactor between the 2 ports DC3_1 & DC3_2, a second contactor between the 2 ports DC3_3 & DC3_4 to double the power limit on 2 charger terminals and a third contactor between the 2 ports DC3_2 & DC3_3 to quadruple the power ratings, modifying the DC3 voltage being done with setpoints sent from the PMS.

Several EVs cannot be connected to a unique Stabiliti™ converter for safety reasons, whereas one EV can be connected to several of them. That is not a real drawback because distributed energy sources and storages on all the Stabiliti™ "belonging" to the same mobility hub are interconnected on the same AC-microgrid. This energy storages and pool of sources in the hub enables EV recharging from all terminals even if some of the storages are fully discharged and even if the energy sources are linked to one specific converter input. The pooling of energy storages and sources has been patented by CE+T as the "Power Fusion" concept allowing to share energy through a DC or AC bus without communication means.

Stabilti Peak Efficiency Paths		
Battery-2-EV	=	**97,3%**
AC-µGrid-2-Evc	=	95%
PV-2-EV	=	96%
PV-2-Battery	=	96,5%
Average Efficiency Figure of Merit	=	**96,1%**
PV-2-Batt-2-EVC	=	**92.5%**

Table 6. Results of efficiencies obtained for the use case with Stabiliti™ multiple port converter.

The evaluation of efficiencies of Figure 5 are given in Table 6. All efficiency paths of the 3-PBC Stabiliti™ are better than the usual approach using 3 kinds of 2-port converters, notably for the global average efficiency but also for the important Battery-2-EVC path having half the losses of usual converter topology. It is interesting to observe that the converter efficiencies are in the same range for both solutions but show sensible differences when looking at the different energy paths, suggesting *that the Stabiliti™ 3-PBC solution surpasses any usual 2-ports converter approach*.

Another interesting feature of the Stabiliti™ system (located on the left side in the Figure 5) is that working in DC/AC grid following mode until the power grid shuts down, then going to grid forming mode would shortly interrupt AC loads on the grid. For mobility hub owners targeting a 24x7 service on site, a solution combining Stabiliti™ and Hercules™ to isolate the local AC-µGrid from the AC power network has been investigated.

EVC with 2 types of 3-port converters for No Break AC-µGrid

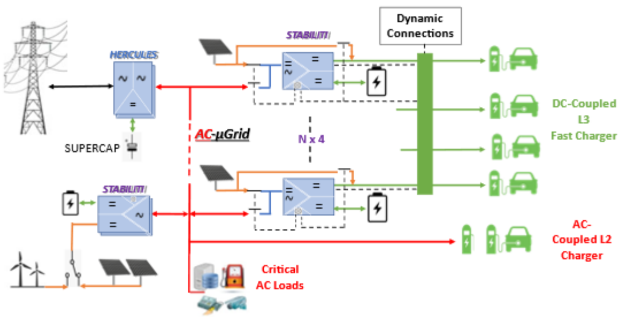

Figure 6. Diagram of a no break charging station made up of AC chargers and DC Fast chargers

The only difference with previous case is that an AC/DC/AC *Hercules™* converter, certified for Grid Interactive CE standard, has been added upstream at the AC power network connection. The super-cap storage suggests a small energy storage that can collect energy from storages in the AC-microgrid thanks to the energy mutualisation. Indeed, *Hercules™* can control the short circuit current for protection selectivity in such a way that downstream protection breakers are triggered within 20ms without opening the main upstream breaker to guarantee a seamless no-break operation for AC critical loads. The AC1/DC2/AC3 has a 96% efficiency between AC1 & AC3 decreasing the µGrid-2-EVC path efficiency but the AC3 output voltage is filtered and controlled at 400Vac, 415V or preferably at 440Vac (below the max working voltage 415V+10%) that increases global efficiency and reliability of all loads & sources on the microgrid feeding all equipment's without harmonic, overvoltage, undervoltage, disturbance, … and increasing the resilience and lifetime of the mobility hub.

CONCLUSION

This white paper has highlighted a unique 3-ports bidirectional converter patented technology demonstrating smart energy routing for EV charging stations. 3-PBC solution provides several advantageous features and possibilities with respect to usual 2-ports approach as:

- a practical implementation of self-consumption,
- a wide voltage ranging up to 1kVdc for all EV types,
- a faster charging time with an EVC power over 200kW
- a high utilisation factor of converters thanks to a switchable port working in AC or DC
- a use in pool of all local energy storages and sources
- ready-made for Vehicle to Grid (V2G) energy transfer
- easy maintenance with one-fits-all type of converter

Moreover, the solution shows a global efficiency that turns out to be better than usual EVC supplied with three different kinds of 2-ports converters. The solution highlighted here is flexible and modular as 3-PBC can easily be parallelized and fit to all EVs with different voltage and power rates.

Decentralized renewable energy is fully part of the solution and AC grid point of connection is highly relieved thanks to the smart use of storages to deliver high charging rates to EVs. The use in pool of all the sources of energy limits all possible congestion at point of connection and upstream in the low voltage distribution network.

REFERENCE

[1] Ali Bahrami, 2020, "EV Charging Definitions, Modes, Levels, Communication Protocols and Applied Standards", *Research Gate*