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Comparison of System Architecture and Converter Topology for a Solar Powered Electric Vehicle Charging Station

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***Abstract*-- Electric vehicles (EV) can be charged in a sustainable way by charging them from photovoltaic (PV) panels. Workplace charging of EV from PV results in use of the solar potential of office buildings and the long parking time at workplace paves way for implementation of vehicle-to-grid (V2G) technology. In this paper, different possible system architecture for an EV-PV charger are investigated and compared. A review of power converters that integrate EV and PV is made and the systems are compared based on system architecture, converter topology, isolation and bidirectional power capability for V2G operation. Based on the study, two optimal designs for the EV-PV charger are proposed that uses a multi-port converter. Different methods to implement modularity in the converter design for charging multiple EVs from a single EV-PV charger are presented.**

***Index Terms* — charging, storage, DC grids, electric vehicle, solar energy**

I. INTRODUCTION

Charging of electric vehicles (EV) from solar energy provides a sustainable method for recharging the car batteries [1]. Workplace like office buildings, factories and industrial area are ideal places to facilitate solar EV charging where the building rooftops and car-parks can be installed with photovoltaic (PV) panels. The generated PV power is directly utilized for EV charging in an EV-PV charger, without the need for storage. A grid connection is necessary to ensure reliable power supply for EV charging due to the variable nature of PV generation. The employee's cars are parked for 6-9h at the workplace and the long charging duration results in low EV charging power requirements and possibility for grid support through Vehicle-to-grid (V2G) technology.

In this paper, different possible system architectures for a solar EV charger are proposed and compared. A review of EV-PV power converters from literature is made and are compared based on the system architecture, converter topology, isolation and capability for V2G operation. The power converter design are correlated with the requirements from global EV charging standards. From this literature survey, two power converter layouts for a 10kW EV-PV charger are proposed – one based on a high frequency three-winding transformer and the second based on a central DC-link. In the last part of the paper, different methods to make the power converter design modular and enable the connection of multiple EV to a single charger are investigated.

II. SYSTEM ARCHITECTURE FOR THE EV-PV SYSTEM

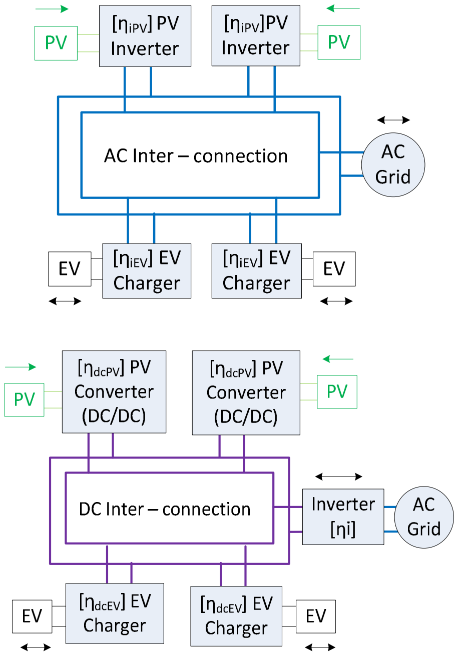

Fig. 1. System Architecture 1 (top) and 2 (bottom) for the EV-PV charger

An EV-PV charger integrates the PV array, the electric vehicle supply equipment (EVSE) and the grid with the main motive to charge the EV directly from the PV power. In Europe, EV charging in the future will be facilitated by DC charging through CHAdeMO and Combined charging standard (CCS) as it facilitates dynamic charging, fast charging and V2X support [2], [3]. Dynamic charging corresponds to using variable charging power i.e. changing the charging power with time. This will enable EV charging to closely follow the variable PV power generation.

To integrate the PV, EV and the grid, two different system layouts are possible [4]:

1. A single multiport converter (MPC) that integrates the grid, PV and EV.
2. Separate power converters for the grid, PV and EV which are interlinked on a common bus.

The common bus is used to share the PV power between different EV and exchange power between the EV and the grid. Using the two system layout mentioned above, the system architecture can be of four types based on whether the interlinking bus is AC (1Φ 230V 50Hz or 3Φ 400V, 50Hz grid) or DC:

A. Separate converter for PV, EV interlinked on AC grid

Fig. 1 shows the schematic of architecture 1. Separate converters are used for the PV panels and for the EV charging/discharging. The PV converter is a DC/AC inverter that incorporates maximum power point tracking (MPPT) and the EV charger is an AC/DC converter. The existing 50Hz AC grid is the backbone of the architecture and all the power is passed via the grid. The disadvantage is that the PV power cannot be directly used in DC form to charge the EV. This necessitates the unnecessary conversion from DC to AC in PV inverter and back from AC to DC in the EV charger.

B. Separate converters for PV, EV interlinked on a DC (micro) grid

Fig. 1 shows the schematic of architecture 2, which uses a DC (micro) grid to interconnect the PV panels, EV and the grid. The PV and EV converters are both DC/DC converters that have MPPT control and charge control respectively. The DC interconnection facilitates the direct use of the DC power of PV for DC charging of EV, which results in higher efficiency [5]–[7]. An (optional) central inverter connects the DC grid with the AC gird and provides for V2G operation and facilitates the feeding/drawing of the power difference between PV generation and EV demand. The disadvantage of the architecture is that the DC (micro) grid has to be constructed and its control and protection has to be incorporated in the design.

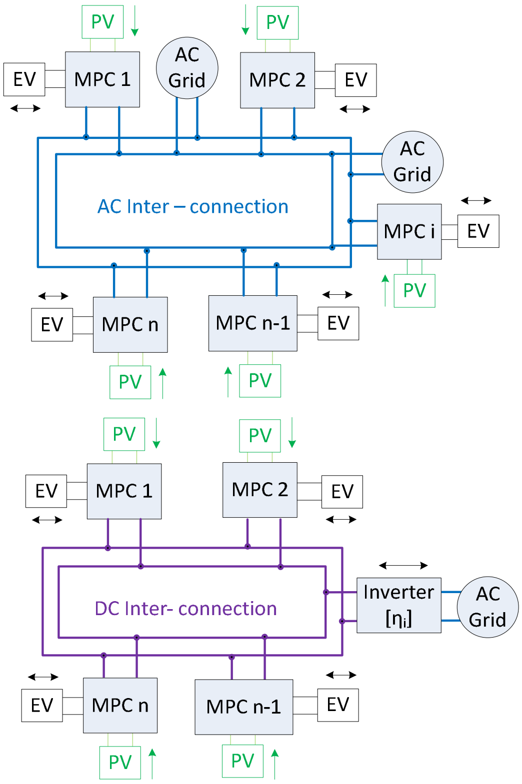

Fig. 2. System Architecture 3(top) and 4(bottom) for the EV-PV charger using multiport converters

C. Multiport converter that integrates the grid, PV and EV; interlinked on the AC grid

Fig. 2 shows the schematic of architecture 3 which uses a multi-port converter (MPC) as shown in Fig. 3. The multi-port converter connects the PV array, the EV and the AC grid using a central DC-link. Multiple MPC are connected to each other via the AC grid. Integration of power electronic converters for PV, EV and grid into one MPC leads to higher power density, cost reduction and ease of control [8], [9]. Control of EV charging from PV can be achieved through the controller of the MPC while in the previous two architecture, communication has to be established between the separate PV and EV converters. The only disadvantage is that the DC PV power from one MPC cannot be used to charge the EV of another MPC without conversion to AC.

D. Multiport converter that integrates the grid, PV and EV; interlinked on a DC (micro) grid

Fig. 2 shows the schematic of architecture 4 which is a combination of architecture 2 and 3. It uses a multi-port converter as shown in Fig. 3 to integrate the PV array and EV. Many MPC are interconnected to each other using a DC (micro) grid. A high power central inverter is used to connect to the AC grid. This central inverter is better than using several small inverters embedded within the MPC as in architecture 3.

E. Comparison of system architectures

TABLE 1 provides a qualitative comparison of the four system architecture. Those marked in red and green indicate the disadvantages and advantages of that architecture respectively. The construction of a separate DC grid and development of its control and protection poses as a disadvantage for the use of architecture 2 and 4. When the DC power of PV is directly used for EV

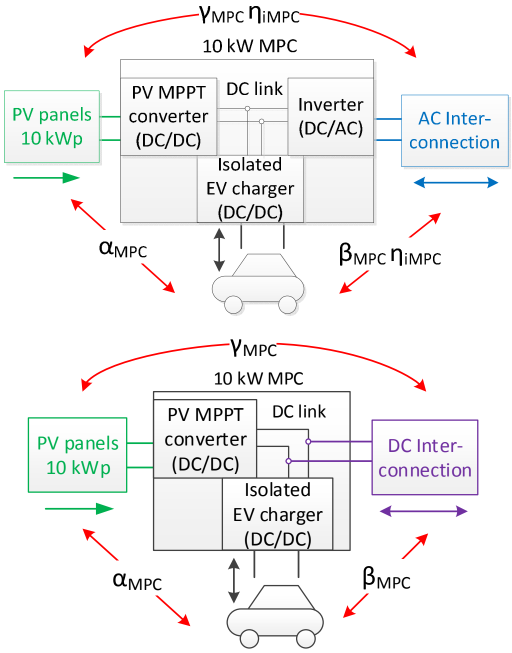

Fig. 3. Block diagram of multiport converter for architecture 3 (top) and 4 (bottom)

TABLE 1
Qualitative comparison of the EV-PV system architectures

	Arch. 1	**Arch. 2**	**Arch. 3**	**Arch. 4**
Construction of DC (micro) grid	No	Yes	No	Yes
Protection and control of DC (micro) grid	No	Yes	No	Yes
Efficiency gain due to direct connection of DC power of EV and PV (with no AC conversion)	No	Yes	Yes	Yes
Possibility of directly using DC power of PV to charge EV between multiple EV-PV chargers	No	Yes	No	Yes
Higher power density and cost reduction due to MPC	No	No	Yes	Yes
Ease of control of EV charging from PV with minimal communication infrastructure	No	No	Yes	Yes

charging in a MPC, it results in higher power density and lower losses as indicated in TABLE 1. It can also be seen from the table that architecture 3 provides several advantages over the other architecture namely the use of MPC, the direct DC connection of EV and PV, ease of control and the usage of the existing AC grid for connection of multiple EV-PV chargers. Hence architecture 3 is the most optimal from the view of qualitative comparison.

There are four possible power flows in an EV-PV charging system, named as mode 1 to 4 in TABLE 2.

1) Mode 1 – Mode 1 is the direct use of PV power for EV charging; which is the main objective of the charging system. Mode 1a is a special case of Mode 1 charging which is applicable for architectures 3 and 4 that uses a MPC. Mode 1a corresponded to the power exchange from the PV panel connected to one EV-PV charger to the EV connected to another EV-PV charger. This could occur in the case of a workplace where EVs are not connected to all EV-PV chargers.

2) Mode 2 – Mode 2 correspond to the power flow from the grid to the EV for EV charging. Mode 2 is used when solar generation is insufficient to meet the EV charging requirements.

3) Mode 3 - Mode 3 correspond to the power exchange from EV to grid for V2X operation.

4) Mode 4 - Mode 4 is used for feeding the PV power directly to the grid. This mode is enabled under the condition that there is no EV for charging or the EV battery is full.

The efficiency of power flows for all the modes for the four system architectures is shown in TABLE 2 and indicated in Fig. 1, Fig. 2 and Fig. 3 where:

α_{MPC} - Efficiency of power conversion between PV and EV in MPC [Arch. 3,4]
β_{MPC} - Efficiency of EV charger in MPC [Arch. 3,4]
γ_{MPC} - Efficiency of PV converter in MPC [Arch. 3,4]
η_{iMPC} - Efficiency of inverter present in MPC [Arch. 3]
η_{dcPV} - Efficiency of DC/DC converter for PV [Arch. 2]
η_{dcEV} - Efficiency of DC/DC converter for EV [Arch. 2]
η_{iPV} - Efficiency of DC/AC inverter for PV [Arch. 1]
η_{iEV} - Efficiency of DC/AC inverter for EV [Arch. 1]
η_i - Efficiency of central inverter [Arch. 2,4]

In comparing the architectures 1 and 2 as per TABLE 2, it can be observed that $\eta_{iPV} < \eta_{dcPV}$ and $\eta_{iEV} < \eta_{dcEV}$ due to lack of power conversion from DC to AC when power flows PV to EV for mode 1. However η_{iEV} will be approximately the same as $(\eta_{dcEV}\,\eta_i)$, i.e. $\eta_{iEV} \approx \eta_{dcEV}\,\eta_i$ for mode 2,3,4 if similar power converter topology is used for the AC EV charger in architecture 1 as compared to the combination of grid inverter and DC EV charger as used in architecture 1. So the gains in efficiency due to direct DC power consumption for architecture 2 are restricted solely to mode 1, with the need to construct an additional DC-grid.

In contrast, architecture 3 provides the benefit of higher conversion efficiency for mode 1 without the use of a DC grid as $\alpha_{MPC} \approx (\eta_{dcPV}\,\eta_{dcEV})$ and $\alpha_{MPC} > \eta_{iEV}\,\eta_{iPV}$. This makes architecture 3 more suitable than both 1 and 2. For architecture 3 and 4, $(\gamma_{MPC}\,\beta_{MPC}) \approx \alpha_{MPC}$. With the advent of future DC (micro) grids [10], architecture 4 will be more attractive than 3 due to improved efficiency for energy exchange between EV and PV of multiple EV-PV chargers in the neighborhood.

From the above comparative analysis, it can be concluded that architecture 3 is the most optimal from both the qualitative (TABLE 1) and quantitative perspective (TABLE 2).

It must be noted that the ohmic losses in conductors is neglected here in the comparison as the physical location of PV and EV will be the same irrespective of the type of architecture used. What will differ is the location of the converters.

III. Comparison Of Power Converter Topology For EV-PV Charger

To design a highly efficient EV-PV charger it is vital to have minimum conversion stages between the PV panels and the EV. DC interconnection between PV and EV is one means to achieve this. The EV charging standards [2], [3] necessitate the isolation of the EV charger both from PV and grid. Further, the use of a bidirectional EV charger facilitates the implementation of V2G technology. In this section, EV-PV chargers that have been published in earlier works are compared in TABLE **3** based on the system architecture, power rating of EV and PV, isolation and bidirectional power flow capability of EV charger and power converter topology.

It can be seen from TABLE **3** that research work in EV-PV chargers have been focused on all four different system architecture. For architecture 1, the use of standard commercially available AC EV chargers and PV inverters is common.

TABLE 2

COMPARISON OF THE CONVERSION STAGES AND EFFICIENCY FOR DIFFERENT EV-PV SYSTEM ARCHITECTURES

Mode	**Power Flow**	**Arch. 1**	**Arch. 2**	**Arch. 3**	**Arch. 4**
1	PV power → EV charging	$\eta_{iPV}\ \eta_{iEV}$	$\eta_{dcPV}\ \eta_{dcEV}$	α_{MPC}	α_{MPC}
1a	PV power → EV charging (Between multiple EV-PV chargers)			$(\gamma_{MPC}\ \eta_{iMPC}\ \eta_{iMPC}\ \beta_{MPC}) = \alpha_{MPC}\ (\eta i_{MPC})^2$	$\gamma_{MPC}\ \beta_{MPC} \approx \alpha_{MPC}$
2	Grid power → EV charging	η_{iEV}	$\eta_{dcEV}\ \eta_i$	$\beta_{MPC}\ \eta_{iMPC}$	$\beta_{MPC}\ \eta_i$
3	EV power → Grid charging	η_{iEV}	$\eta_{dcEV}\ \eta_i$	$\beta_{MPC}\ \eta_{iMPC}$	$\beta_{MPC}\ \eta_i$
4	PV power → Grid charging	η_{iPV}	$\eta_{dcPV}\ \eta_i$	$\gamma_{MPC}\ \eta_{iMPC}$	$\gamma_{MPC}\ \eta_i$

TABLE 3

COMPARISON OF TOPOLOGY, SYSTEM ARCHITECTURE AND EV CHARGER DESIGN FROM LITERATURE

Paper	**System Arch.**	**[PV, EV] Power (kW)**	**EV Isolation/ Bidirectional charging**		**Power converter topology & design**
[11]	1	[2.1, 2.4]	-	-	Standard PV inverter of 93% efficiency used. Standard AC EV charger used.
[12]	1	[1, -]	-	-	EV bike charging with local storage.
[13]	1	[51.5, 3.5]	-	-	Standard AC EV charger and SMA Sunnyboy PV inverters are used.
[14]	1	[5.1, 7]	-	Yes	Modified industrial variable speed drive with a full-bridge topology used as bidirectional converter for EV (V2G possible).
[15]	1	[47, -]	-	-	Standard AC EV charger and PV inverters used.
[16]	1	[13, 2]	-	-	Boost converter for PV charges 70kWh local storage and 1-phase inverter feeds PV power to grid. Standard AC charger used for EV charging.
[17]	1	[8.2, 2]	-	-	Bidirectional DC/DC converter charges local storage from PV and H bridge inverter feeds PV power to grid. Standard AC charger used for EV charging.
[18]	1	[9.2, -]	-	-	Grid connected inverters feed PV power to grid. Standard AC charger used for EV charging.
[19]	1	[3.6, <22]	-	No	PV inverters and standard AC EV chargers used. EV charging powers of 3.7kW, 7kW, 11kW and 22kW are compared and 3.7kW shows maximum utilization of PV power for EV charging.
[5], [6]	2	[4x1.2, 2x4]	No	No	Direct DC charging of EV from PV. ZVT-PWM buck converter for PV and EV and separate 5kW inverter, 8kW rectifier for grid are all interlinked on 210V DC bus. Up to 5% improved efficiency compared to architecture 1.
[20], [21]	2	[100, -]	-	-	Direct DC charging of EV from PV using common DC bus.
[22], [23]	2	[25, 10]	No	Yes	10kW DC/DC converter with zero voltage switching quasi square-wave (ZVS-QSW) switching at 98% efficiency used for EV charging. 575V central DC link interconnects PV and EV converters. Aim is mitigation of solar irradiance intermittency.
[24]	2	[100,430]	No	Yes	Single phase bidirectional DC/DC converters with no isolation are used for PV and EV to connect to a 480V DC grid. AC grid connected voltage source converter (VSC) ensures power balance and stability of system.
[25]	2	[20,60]	No	Yes	
[26]	2	[65, 160/66]	No	No	DC grid of 350V is used to interface EV, PV, grid, fixed storage, wind and dump load. Bidirectional converter connected to fixed storage ensures power balance and voltage stability of DC-grid.
[27]	2	[-, 3]	Yes	Yes	3kW bidirectional contactless charger for EV. Isolation is inherently present due to the air core transformer used.
[28]	2	[9.8, 10]	No	-	Batteries/EV are directly connected on a common DC-link. Buck converter with MPPT connects PV to DC-link.
[29]	~2	[3.8, 3]	No	No	3.3kW direct DC charging of EV from PV at 70% efficiency. Charge controller charges 48V battery from PV. Boost converter connected to 48V battery is used for EV charging.
[30]	~2	[0.4, -]	No	-	Direct DC charging of EV from PV using boost converter. Bidirectional buck/boost converter controls power flow between EV battery and EV motor.

[31], [32]	3	[3.3, 3.3]	No	Yes	3.3kW direct DC charging of EV from PV. MPC with boost converter for PV, H bridge inverter for grid and interleaved buck converter for EV interlinked on 380V DC link. 7% to 15% improved efficiency compared to architecture 1.
[33]	3	[5, 10]	Yes	Yes	Symmetrically isolated Z-source converter used for EV charging from PV. Comparison with transformer-less and high-frequency transformer isolated topologies for PV indicates that transformer-less topology exhibits highest efficiency of up to 97%.
[34]	3	[5, 6]	No	Yes	Quasi-Z-source inverter with 680V DC link and 3Φ grid connection. 96kWh local storage integrated into EV-PV charger. 4 EV chargers can be active simultaneously.
[35]	3	[2, 2]	No	Yes	Quasi-Z-source inverter with 350V DC link and 3Φ grid connection. Converter designed for battery charging (and not for EV).
[36], [37]	3	[5.5, 4.5]	No	No	MPC made of Boost converter for PV, 1-phase H-bridge inverter for grid and buck converter for EV interlinked on 400V DC link.
[38]	~3	[, 10]	No	Yes	Z-source converter for charging EV from PV. 3Φ bidirectional inverter connects EV to grid.
[9]	4	-	No	Yes	Three port converter for PV, battery and load. Load is isolated. Designed for battery charging application (Not specifically for EV).
[8]	4	-	No	Yes	Four port converter for PV, battery, wind and load. Load is isolated. Designed for battery charging application (Not specifically for EV).
[39]	4	-	Yes	Yes	Three port isolated DC-DC-DC converter using a high frequency AC transformer link.
[7]	1,3	[20, 3]	-	-	Direct charging of EV from PV DC/DC converter at 90% efficiency. No converter for PV; DC-AC-DC charging results in 40% losses.
[40]	~ 1, 3	[1.9, 3.2]	-	-	MPC with isolation for integrating local storage, PV and grid. EV charged from AC grid using AC charging stand.
[41]	1, 2	-	Yes	-	Contactless charging of EV from PV. Isolation is inherently provided by the air core transformer of the inductive power transfer (IPT) system.

Many publically available PV powered EV charging station like [13], [15] are based on this simple architecture. Architecture 4 has been the least explored, most reasonably because of its use of a futuristic DC grid. [8], [9] which use a PV system to charge batteries is indirectly based on the use of architecture 4. The DC load port of the converter in [8], [9] can be connected to a central DC-grid and an isolated DC converter can be used for the battery charger to enable it for EV charging. Buck or boost converter are most commonly used topology for the PV converter and EV charger.

An important observation is that except for [27], [33], none of the other design have implemented a bidirectional EV charger with isolation. The isolation requirements for the EV has been neglected or not addressed in almost all research works except [27], [33], [41]. In case of [27], [41], the isolation indirectly stems from the use of air core transformer for the contactless charging of the EV.

IV. Power Converter Topology For EV-PV Charger

Based on the comparison of EV-PV system architecture and power converter topologies, two suitable MPC topologies for a 10kW EV-PV charger based on architecture 3 is shown in Fig. 4. 10kW is chosen as the charging power based on the draft proposal of CHAdeMO standard to implement 10kW of bidirectional charging and V2X operation. In the first topology A, a three winding high frequency transformer is used to integrate the EV, PV and grid [39]. The advantage is that the design provides isolation between all three ports. The drawback of the topology is threefold - a bidirectional port at the PV is unnecessary and the power flow path from PV to grid has three conversion stages, DC→AC→DC→AC. Further as per European standards, isolation is not required in the current flow path from the PV to grid.

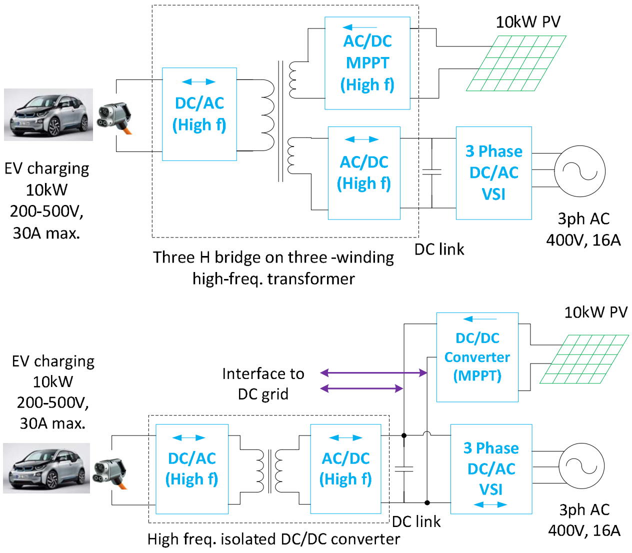

Fig. 4. Block diagram of multiport converter topology A (top) and B (bottom) based on architecture 3

So the use of a transformer based AC link leads to additional losses than can be avoided.

In the second topology B in Fig. 4, a central DC link within the MPC interconnects the EV, PV array and the grid. A three leg inverter connects the DC link with the three phase grid providing up to 11kW power (3ph 400V, 16A). The DC link must be rated above the peak voltage of the three phase grid i.e. > $400\sqrt{2}$. A high frequency transformer isolated DC/DC converter is embedded in the MPC for the EV charging. Since the Z-source converter has complicated control [33], a suitable topology for the isolated DC/DC converter for EV charging is the bidirectional series resonant converter and the dual active bridge with soft switching, based on the analysis in [42]. A non-isolated DC/DC converter is used for the MPPT of the PV array. An interleaved boost converter would be optimal to connect a $10kW_p$ PV array to the DC-link of the MPC [43]. A major advantage of this MPC topology is that the DC link can be used (in future) to connect to a DC grid and to integrate a local battery storage. Thus it provides the flexibility to be a used in both architecture 3 and 4.

From the assessment above, topology B is hence preferred over A for the design of the MPC for architecture 3.

V. CONNECTING MULTIPLE EVS TO AN EV-PV CHARGER

A modular converter topology facilitates the integration of additional sources and loads. For the EV-PV charger, the ability to integrate more EV into one charger will provide for a flexible design. For example, at a workplace, it would be convenient for the EV owner to plug the car for charging in the morning, irrespective of how long the charging would take. With long parking times of 8h at workplace, having one 10kW charger per car will be unnecessary as charging requirements would be less than 8h*10kW=80kWh on a daily basis. It would be beneficial to look into methods by which multiple cars can be connected to a single charger in a modular way. This section proposes different methods to implement modularity on the EV-PV converter design. Important consideration is that the EV must be isolated from the grid, PV and another EV during charging/V2X operation.

A. Strategy 1 – Using multiple charging plugs with DC disconnectors

Multiple CHAdeMO and CCS charging ports can be connected to a single EV-PV charger as shown in Fig. 5. At any point of time, only one of these charging ports is delivering power to the EV while the rest are separated using DC disconnectors. This ensures that the EVs are isolated from each other during charging. To start charging of a new car B while a car A is already charging, can be done by:

i. Reducing the charging power of car A to zero and then stop charging
ii. Open DC disconnector of car A and then close the disconnector of car B
iii. Initiate the charging of car B

B. Strategy 2 – Using multiple isolated DC/DC converters connected on DC link

Multiple DC/DC converters with isolation can be connected on the DC link of a single EV-PV charger as shown in Fig. 5. The advantage is more than one EV can be charging/discharging simultaneously as long as they are within the maximum power limit of 10kW. A three phase grid connection of 32A can facilitate a combined charging of up to 22kW.

C. Strategy 3 – Multi-winding high frequency transformer on DC-link

Multi-winding high frequency transformer as mentioned in topology A can be used in the EV-PV charger as shown in Fig. 5. Each EV can be connected to one of the transformer winding. Similar to strategy 2, the advantage is that multiple EV can be charging or discharging simultaneously. The challenge lies in the design of the multi-winding transformer and its control. While the charging of multiple EV is possible with this strategy, the drawback is that the design is not modular.

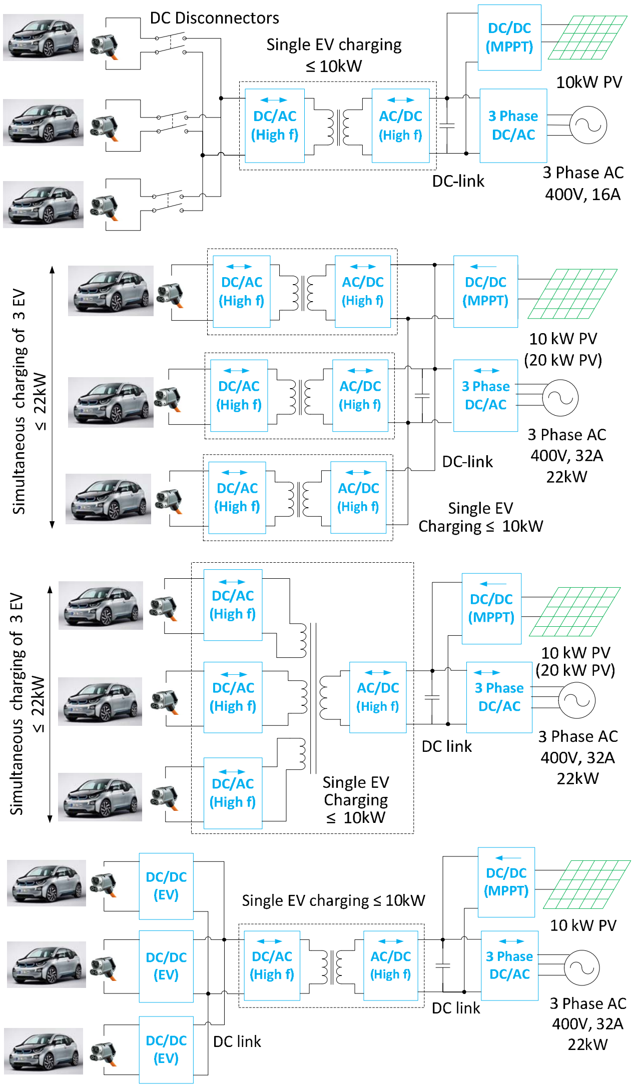

Fig. 5 – Strategy 1,2,3 and 4 (top to down) for connecting multiple EV to a single EV-PV charger

The transformer and control have to be redesigned based on the number of EV that need to be connected.

D. Strategy 4 – Multiple DC/DC converters at output

Multiple DC/DC converters without isolation can be connected at the DC output of the EV-PV charger as shown in Fig. 5. This is simpler than strategy 2, which requires multiple isolated DC/DC converters to ensure isolation of EV is from grid and PV. However, the major shortcoming of strategy 4 is the lack of isolation between one EV and another. As long as isolation between the cars is required as per the charging standards [2], [3], this strategy will not be technically feasible for simultaneous charging of EV.

Based on the above examination, it can be observed that strategy 1 is most optimal for integrating multiple EV to a single EV-PV charger. If simultaneous charging of EV is required, strategy 2 should be implemented.

VI. CONCLUSIONS

Different system architectures and power converter topologies for a solar powered EV charging station are analyzed and compared. Architecture 3 which uses a three-port converter that connects to the EV, PV and grid provides several advantages over the other architecture - direct use of DC power of PV for EV charging, the ease of control and higher power density that is achieved due to the use of an integrated converter and the usage of the existing AC grid for connection of multiple EV-PV chargers.

In Europe, EV charging in the future will be facilitated by DC charging through CHAdeMO and Combined charging standard as it facilitates dynamic charging, fast charging and V2X support. An analysis of published research work in the field of EV-PV charging shows that isolation and bidirectional capability of the EV charger has been neglected by most works. Focus has been mainly on architectures 1 and 2 where separate converters are used for PV and EV.

Multi-port converters (MPC) are gaining attention currently and will be the direction of research for future designs of solar powered EV charging station. MPC can have power flow via a central DC-link or via high frequency transformer AC link. Due to lower number of conversion stages for power flow from PV→grid and since isolation is not required in Europe between PV and grid, the central DC-link based MPC is preferred.

Connecting multiple EV to a single EV-PV charger provides flexibility of charging at workplace. This can be achieved by using DC disconnectors or several isolated DC/DC converters on the central DC-link to realize a modular design.

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