Modularized, Reconfigurable and Bidirectional Charging Infrastructure for Electric Vehicles with Silicon Carbide Power Electronics (MoReSiC)

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Title: "Additional function of the PFLC taking into account photovoltaic extension"

Authors: Krzysztof Kalinowski, Rafał Miśkiewicz, Rafał Kopacz, Jacek Rąbkowski, Warsaw University of Technology

Executive summary

The deliverable includes the description of the vehicle charging system with detailed information about the signals sent and received by the main controller to the microcontrollers implemented in each power converter in the system. This deliverable also contains all of the possible operating modes defined and analyzed with the proper mathematical description of power flow within the system. Moreover, the energy management flowchart-based algorithm is presented. The deliverable is further improved with all the additional operation modes, possible through the inclusion of the photovoltaic converter.

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1. Description of the vehicle charging system with EV energy storage

The experimental system designed for the project consists of a three-level active rectifier with a three-port DC output, which is designed to supply energy to the charging infrastructure or return it to the grid. Moreover, there is a non-isolated three-level DC-DC converter that enables bi-directional energy flow from the energy storage to electric vehicle and grid. There are also two isolated DC/DC converters, which can operate up to 10 kW power independently, charging several cars simultaneously. There is also a possibility of reconfigurating the outputs for parallel operation and enabling fast charging of one electric vehicle up to 20 kW. All converters in the system have the character of a bidirectional energy flow, which generates many operating modes and a varied power flow. The block diagram of the electric vehicle charging system (ECS) with the energy storage (ES) is shown in Figure 1. The correct definition of the operating modes enables a trouble-free transition between them. Operating modes can be classified into two categories: during regular operation of the system and those that require reconfiguration by stopping the system. The type of converters used, together with possible algorithms, are presented in the following chapters.

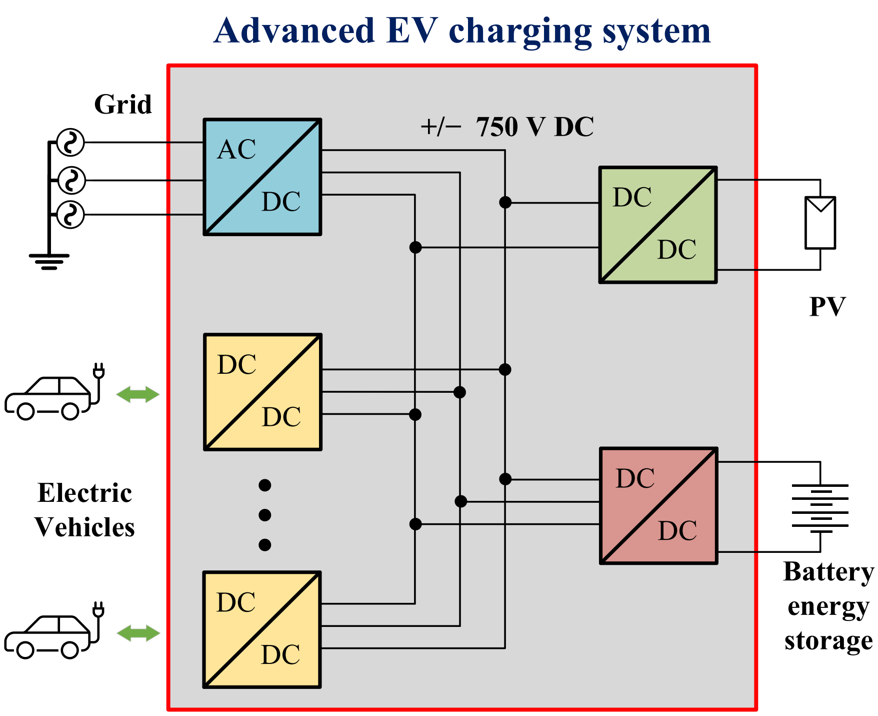

Fig. 1 Scheme of the advanced EV charging system with energy storage and photovoltaics integration.

1.1 Active Rectifier (Three-level AC/DC converter)

The block diagram of the active rectifier based on the ANPC submodule is shown in Figure 2.

The basic tasks of the converter control algorithm are:

- Voltage stabilization in the DC circuit and its balancing with the three-port output. In this case, the power flow is determined by changes in the above voltage. The algorithm responds to the voltage changes and supplies power to the mains or receiver. The above is done with the unit power factor and the reduction of the higher harmonics of the grid current.
- The second operating mode is active and reactive power control. This mode of operation is possible, provided that another system converter stabilizes and balances the voltage in the DC link. This enables the setting of active and reactive inductive or capacitive power, provided that the apparent power does not exceed the design power of the converter.

Reference values, such as the voltage set in the DC link and active or reactive power, are sent via the CAN network.

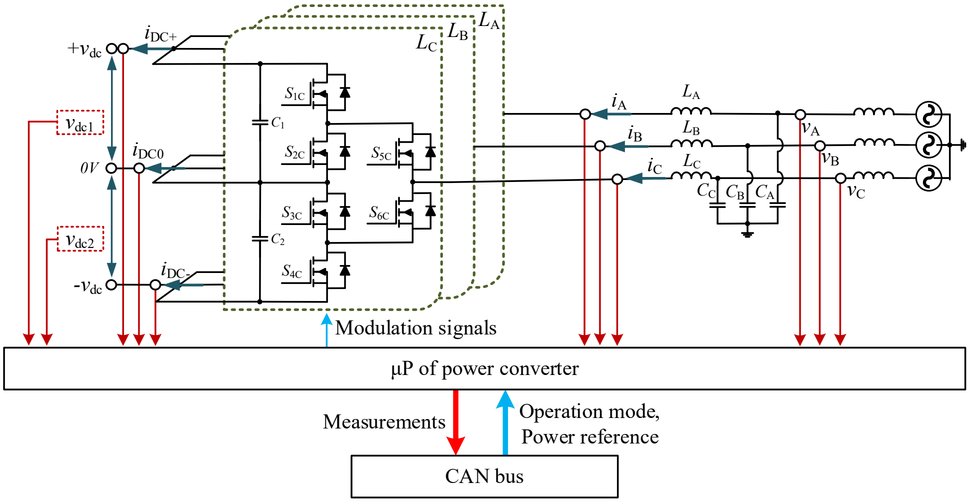

Fig. 2 Structure of the grid converter based on ANPC topology

1.2 Non-isolated DC/DC converter (niDC/DC)

The block diagram of the DC/DC non-isolated converter ES is shown in Figure 3.

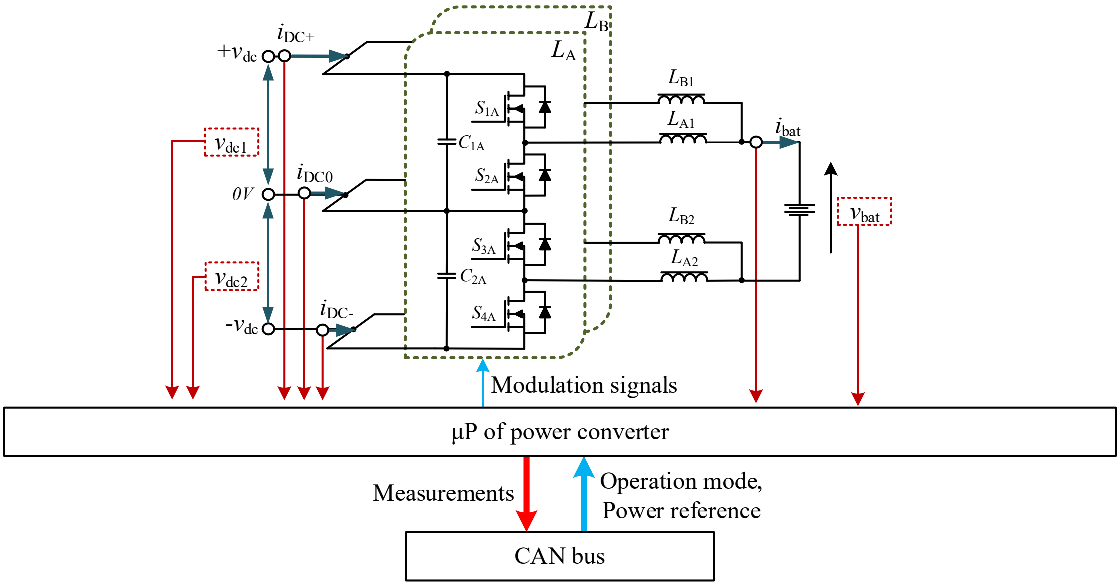

Fig. 3 Structure of the two-phase, three-level DC/DC converter for energy storage

The basic tasks of the converter control algorithm are:

- Controlling the charging and discharging power of the energy storage. This power is limited by the state of charge of the energy store. The reference values can be charging current/battery power or maximum voltage. These values result from the battery energy storage charging modes such as Constant Voltage and Constant Current. The change of energy direction is made by the voltage working mode from step-up/step-down.
- Stabilization and balancing of the voltage in the DC-link. As in the case of an active rectifier, the algorithm responds to voltage changes and changes the direction of power flow.

1.3 Isolated DC/DC converters for EVs (iDC/DC)

The block diagram of the isolated DC/DC converter EV charger is shown in Figure 4.

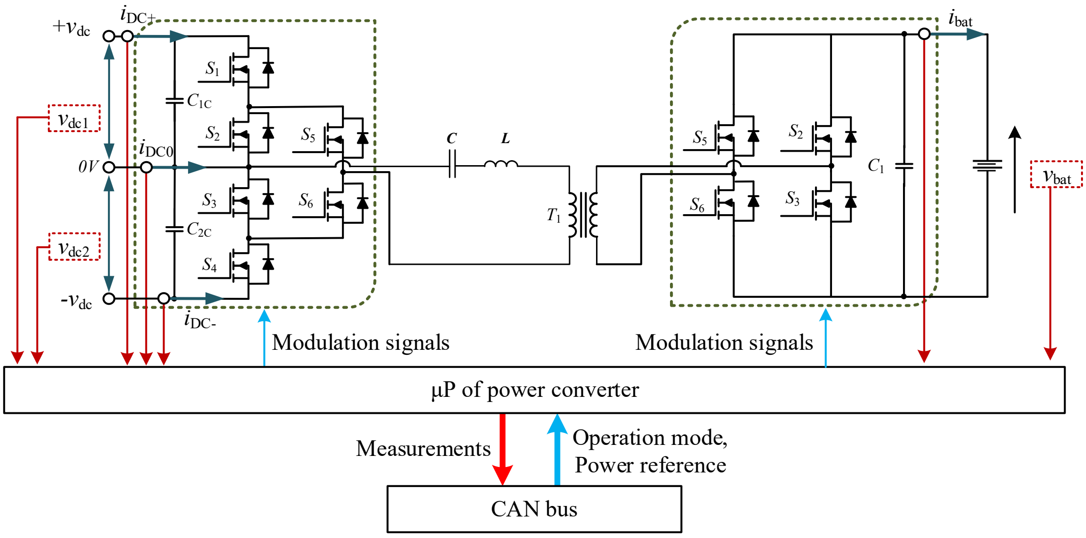

Fig. 4 Structure of the isolated DC/DC converter for charging the EV

The basic tasks of the converter control algorithm are:

- Controlling the charging and discharging power of the EV battery. This power is limited by the state of charge of the battery. The reference values can be charging current/battery power or maximum voltage. These values result from the charging modes of the battery energy storage, such as Constant voltage and Constant Current. The change of energy direction is made by the voltage working mode from boost /down.
- Stabilization and balancing of the voltage in the DC-link. As in the case of an active rectifier, the algorithm responds to voltage changes and changes the direction of power flow.

1.4 Non-isolated DC/DC converter for PV integration (pvDC/DC)

The block diagram of the non-isolated DC/DC converter for PV integration is shown in Figure 5.

The basic tasks of the converter control algorithm are:

- Controlling the voltage of the PV side in order to maximize power output from the PV panel according to MPPT (maximum power point tracking) and transferring the power further into the station.

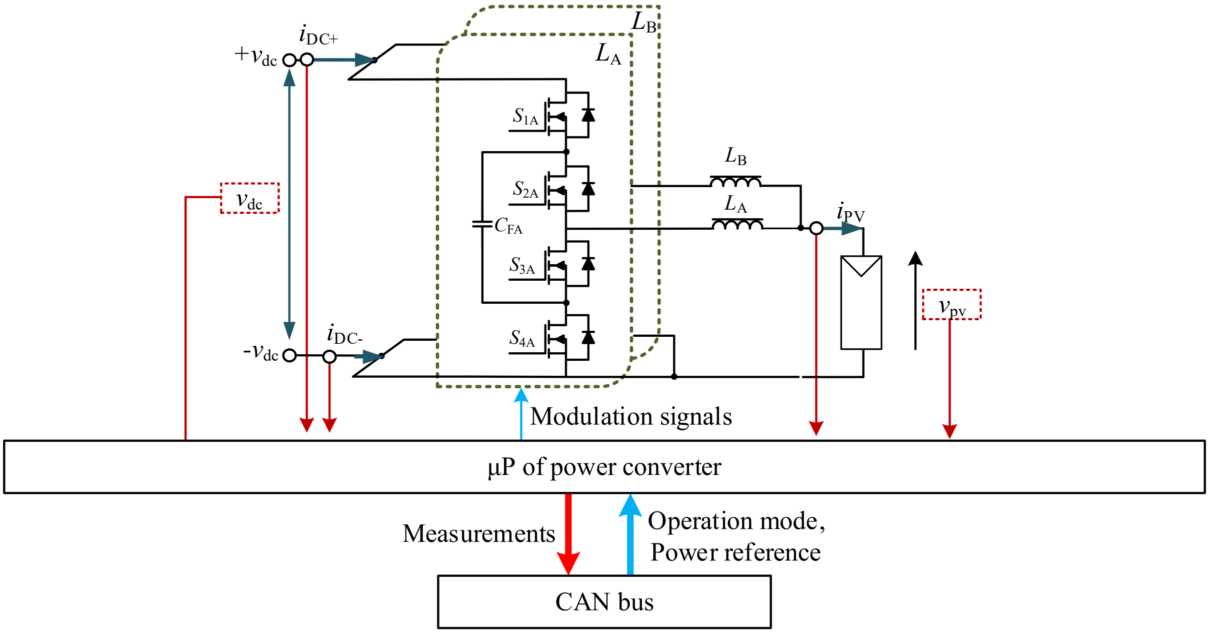

Fig. 5 Structure of the non-isolated DC/DC converter for PV integration.

2. Description of the operating modes

The presented system is capable of a few different operation modes, in which every one of them is responsible for different energy transfer and power flow in the system, as depicted in Fig. 5. The scenarios can be divided into six basic modes, based on the current aim of station operation, as shown in Table I. These are further expanded to incorporate the later added PV inclusion with the basic mode variants (noted with + and −, e.g., mode A+). The extended operation modes are showcased in Table II.

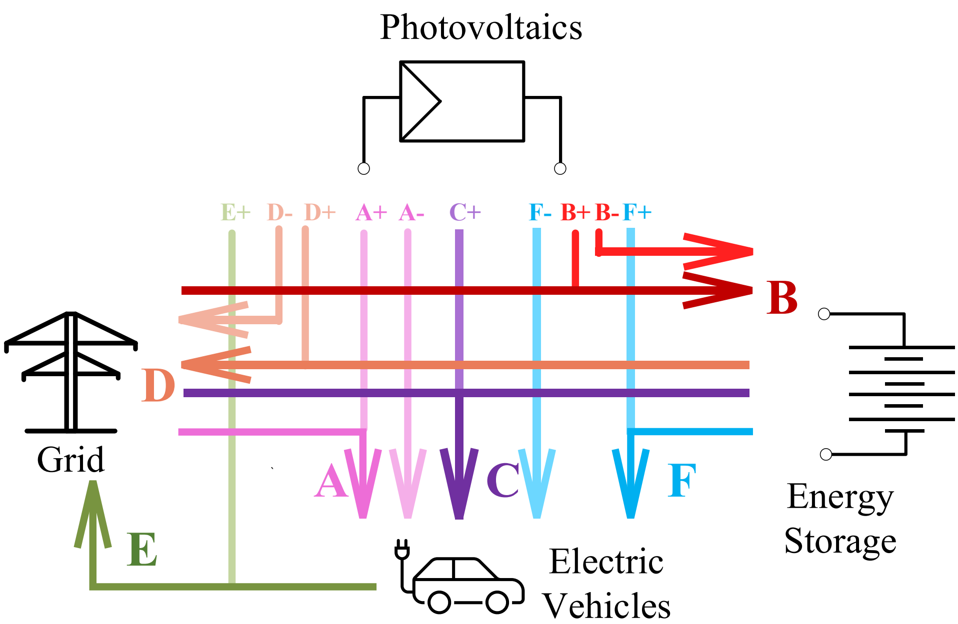

Fig. 5 Schematic operation modes in the system

TABLE I Basic operation modes of the system.

Mode	Description
A	EV slow charging (from the grid)
B	ES slow charging (from the grid)
C	EV fast charging (from the grid and ES)
D	Grid support (from ES)
E	Grid support from vehicles (V2G)
F	Stand-alone / Grid fault

TABLE III Extended operation modes with PV.

Mode	Description
A-	$P_{EV}^{*} \leq P_{PV} \Rightarrow P_{EV}^{*} = P_{PV}$
A+	$P_{EV}^{*} > P_{PV} \Rightarrow P_{EV}^{*} = P_{PV} + P_{GRID}$
B-	$P_{ES}^{*} \leq P_{PV} \Rightarrow P_{ES}^{*} = P_{PV}$
B+	G$P_{EV}^{*} > P_{PV} \Rightarrow P_{ES}^{*} = P_{PV} + P_{GRID}$
C+	$P_{EV}^{*} = P_{GRID} + P_{ES} + P_{PV}$
D+	$P_{GRID}^{*} = P_{ES} + P_{PV}$
E+	$P_{GRID}^{*} = P_{EV} + P_{PV}$
F+	$P_{EV}^{*} > P_{PV} \Rightarrow P_{EV}^{*} = P_{ES} + P_{PV}$

All the modes are described in detail below.

1. Energy is transferred from the grid to the electric vehicles – EV direct charging (A),
    a. Energy is transferred from the grid to the electric vehicles with partial support from PV according to its availability (A+),
    b. Energy is transferred exclusively from the PV to the electric vehicles (A-);
2. Energy storage is charged from the grid (B),
    a. Energy storage is charged from the grid with support from PV, according to its availability (B+),
    b. Energy storage is charged exclusively from the PV (B-);
3. Energy is transferred from the grid and energy storage to enable fast charging (C),
    a. Energy is transferred from the grid and energy storage to enable fast charging with partial support from PV, according to its availability (C+);
4. Energy storage supports grid (D),
    a. Grid support from the energy storage and PV (D+),
5. Energy from the Electric Vehicle is transferred to the grid V2G (E),
    a. Grid support from the energy storage and electric vehicles (E+);

6. Energy is gathered from the previously charged stationary energy storage and provided to the electric vehicle without the grid (island operation) – (F),
    a. Off-grid operation with the power transferred from the energy storage and PV to the electric vehicles (F+).

2.1.1 Slow Charging from grid (P=<10 kW) (A)

The system is configured as follows: The active rectifier AC/DC converter is on and works in DC voltage stabilization mode. One electric vehicle charger (isolated iDC/DC converter) also operates up to its maximum power of 10 kW. The energy storage converter (non-isolated DC/DC) niDC/DC converter remains off. The power flow algorithm does not consider the converters' efficiency.

$$P_{AC/DC} = 0\ kW > (P_{iDC/DC})\ 10\ kW$$

2.1.2 Slow Charging from grid and PV (P=<10 kW) (A+)

The system is configured as in the previous mode, except that the power, when available, is preferably drawn from the PV plant, and the remaining required power is delivered from the grid.

$$P_{AC/DC} + P_{PV} = 0\ kW > (P_{iDC/DC}) < 10\ kW$$

2.1.3 Slow Charging exclusively from PV (P=<10 kW) (A-)

Again, the EV is charged slowly (up to 10 kW). However, in this scenario, the power is drawn exclusively from the PV, assuming that it meets the whole power demand from the EV.

$$P_{PV} = 0\ kW > (P_{iDC/DC}) < 10\ kW$$

2.2.1 Charging of the ES (P=<20 kW) (B)

In this mode, the system is configured as follows. The power is delivered from the grid to the energy storage up to the converter's capability of 20 kW. The grid converter is set to balance the DC-link voltages if needed.

$$P_{niDC/DC} = 0\ kW > P_{AC/DC} < 20\ kW$$

2.2.2 Charging of the ES supported by PV (P=<20 kW) (B+)

In this case, the power is delivered from the grid to the energy storage up to the converter's capability of 20 kW, while, according to the availability, the power is preferably drawn from the PV plant, and the remaining required power is delivered from the grid. The grid converter is set to balance the DC-link voltages if needed.

$$P_{niDC/DC} = 0\ kW > (P_{AC/DC} + P_{PV}) < 20\ kW$$

2.2.3 Charging of the ES exclusively from PV (P=<10 kW) (B-)

This mode is an alternative in which the PV meets the whole power demand from the ES, and the grid converter is off. In this case, the ES converter is responsible for keeping the DC-link voltages balanced.

$$P_{niDC/DC} = 0\ kW > P_{PV} < 10\ kW$$

2.3.1 Fast charging from Grid and ES (P=<20 kW) (C)

In this scenario, the EV converters are connected in parallel to extend the power capability for EV charging, which is up to 20 kW in the experimental model. However, note that power could be easily expedited with parallel connection of more EV converters. To be more specific, in the mode, the active rectifier is enabled in DC-link voltage stabilization mode. Furthermore, the niDC/DC energy storage converter is turned on, and the power is drawn from both ES and the grid. This can be further optimized according to the energy availability and cost. In the experimental system, this is limited to 20 kW (two 10 kW EV chargers).

$$P_{AC/DC} + P_{niDC/DC} = 0\ kW > \left(P_{iDC/DC1} + P_{iDC/DC2}\right) < 20\ kW$$

2.3.2 Fast charging from Grid, ES, and PV (P=<20 kW) (C+)

This mode is a variation of the previous one. As depicted in the earlier mode, the EV converters are connected in parallel to extend the power capability for EV charging, which is up to 20 kW in the experimental model. The active rectifier is enabled in DC-link voltage stabilization mode, and the niDC/DC energy storage converter is turned on. Here, PV is also enabled and acts as an energy source. Thus, power is drawn from PV, ES, and the grid. Cost optimization is crucial in this operating mode. While conceptually, the power could be really high here with several units in parallel, in the experimental system, this is still limited to 20 kW (there are two 10 kW EV chargers).

$$P_{AC/DC} + P_{niDC/DC} + P_{PV} = 0\ kW > \left(P_{iDC/DC1} + P_{iDC/DC2}\right) < 20\ kW$$

2.4.1 Grid support from ES (P=<20 kW) (D)

Here, the power flow is from the ES to the grid, supporting the electric system. The grid converter is set to balance the DC-link voltages.

$$P_{AC/DC} = 0 \leq P_{niDC/DC} \leq 20\ kW$$

2.4.1 Grid support from ES and PV (P=<20 kW) (D+)

Again, the D+ mode is an offspring of mode D. However, here, when available, the energy is preferably drawn from the PV plant, and only the rest is supplied by the ES.

$$P_{AC/DC} = 0 \leq (P_{niDC/DC} + P_{PV}) \leq 20\ kW$$

2.5.1 Vehicle-to-grid (V2G) operation (P=<20 kW) (E)

The system configuration is as follows: Active AC/DC rectifier is enabled in DC voltage stabilization mode. The niDC/DC energy storage converter is disabled. iDC/DC vehicle chargers work in slow mode and can return the energy to the grid.

$$P_{AC/DC} = 0 \leq (P_{iDC/DC1} + P_{iDC/DC2}) \leq 20\ kW$$

2.5.2 Vehicle to grid (V2G) operation with PV support (P=<20 kW) (E+)

This further expands the previous mode with the PV converter. When possible, the power is primarily drawn from the PV plant, and only the remaining required power is delivered from the EVs.

$$P_{AC/DC} = 0 \leq [(P_{iDC/DC1} + P_{iDC/DC2}) + P_{PV}] \leq 20\ kW$$

2.6.1 Stand-alone EV charging from ES (P=<20 kW) (F)

The system configuration is as follows. The active AC/DC rectifier is off, or there is no mains (island operation). The niDC/DC energy storage converter is turned on and is in DC voltage stabilization mode. iDC/DC vehicle converters are employed to charge the EVs, given that the total power does not exceed 20 kW (power of the battery converter). The discharge and charging power is also limited by the state of charge of the energy storage.

$$P_{niDC/DC} = 0 \leq (P_{iDC/DC1} + P_{iDC/DC2}) \leq 20\ kW$$

2.6.2 Stand-alone EV charging from ES and PV (P=<20 kW) (F+)

Again, this is a variation of the prior mode. Power is drawn from the PV plant when available. The remaining power is delivered from the ES.

$$P_{niDC/DC} + P_{PV} = 0 \leq (P_{iDC/DC1} + P_{iDC/DC2}) \leq 20\ kW$$

Thus, all possible operation modes, including the new modes appearing in the midst of the addition of the PV converter, are covered. Therefore, Task T1.1, "Analysis of the various scenarios in EV charging stations," has been completed.

3 The basis of the power flow algorithm

In the experimental model of the charging system designed in the MoReSiC project, there are five power converters, and the main central unit responsible for power management is required. In the discussed concept, two essential blocks are proposed: mode selector and mode decoder (Fig. 6). The first block is based on digital signals gathered from all the converters, the supply grid, the PV plant, and the energy storage – all proposed signals are collected in Table III. The main function is to determine the current operation mode on the base of the acquired signals. The signal flow and decision-making process are illustrated in Fig. 7. In practice, this part can operate in the timer-triggered loop interrupted by the state changes of the signals. On the basis of defined modes from A to F (with + and – variations), which were described earlier, the mode decoder alters it into proper control signals for the power converters: reference value of the voltage in the DC-link and reference power. According to the actual mode, the DC voltage can be controlled by the AC/DC converter (i.e., in modes A, B, or C) by the non-isolated DC-DC converter cooperating with the energy storage (in mode F).

TABLE III Signal inputs to the system.

Signal	Description
EVCR	EV charging request
FCR	EV Fast charging request
ESCR	Energy Storage charging request
GD	Grid demand
ESA	Energy Storage available
PVA	Photovoltaics available
GA	Grid available
V2Gx	Vehicle-to-Grid operation availability

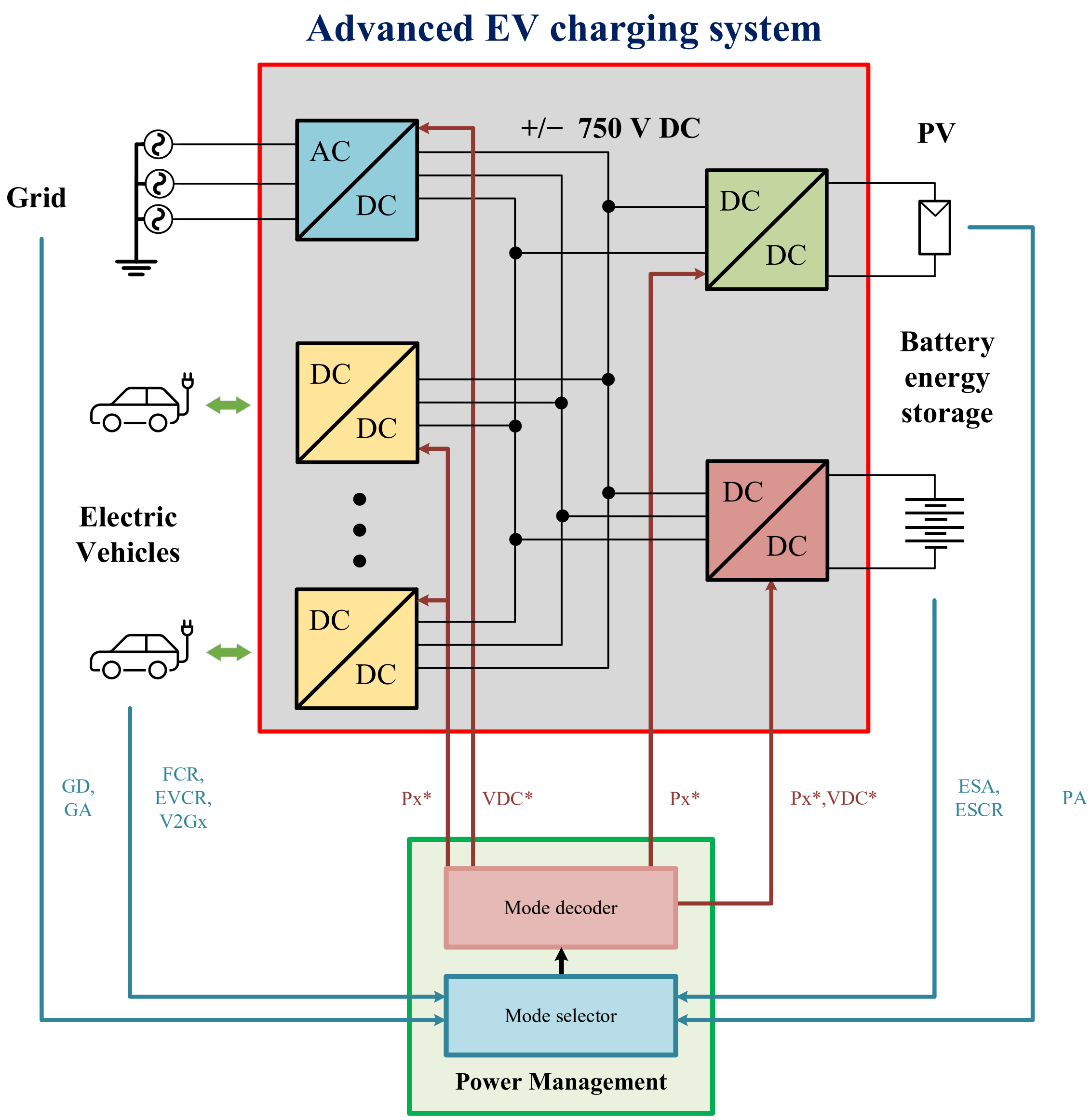

Fig. 6 Fast charging system with the main control unit.

The algorithm for controlling the energy flow in the presented system is shown in a general form in Figure 7. It is divided into four procedures: slow charging of electric vehicles, fast charging of electric vehicles, charging of energy storage, and operating as a storage facility providing grid services.

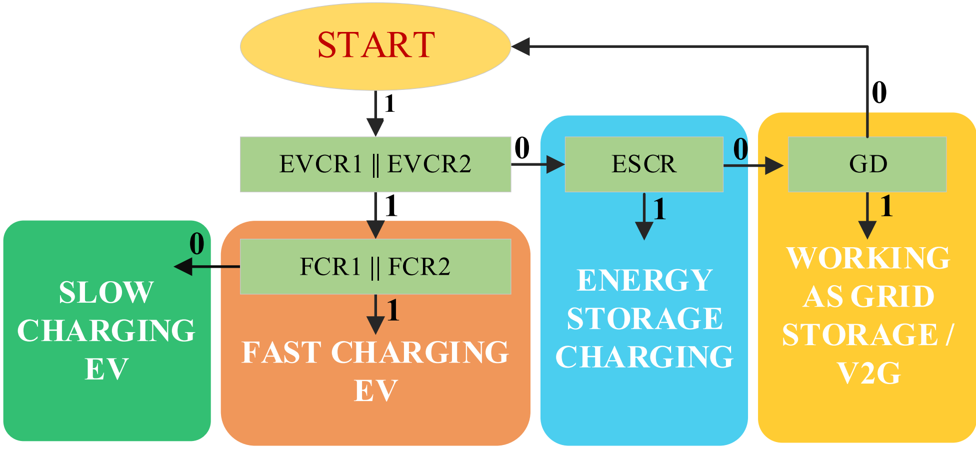

Fig. 7 Simplified flowchart of the algorithm – division into individual procedures.

In principle, the main goal of an electric vehicle charging infrastructure is to charge EVs. Therefore, the first (and the most important) condition is to check whether there is a demand for charging (EVCR). If so, the signal responsible for checking whether fast charging is required is checked next (FCR). If its value is positive (FCR = 1), the system switches to a procedure corresponding to fast charging. If not (FCR = 0), the slow charging procedure is carried out.

When there is no charging demand (EVCR = 0), the algorithm proceeds to the energy storage charging procedure. Here, the ESCR signal is checked, which defines whether the energy storage needs to be charged. If so (ESCR = 1), the algorithm remains in this procedure. If not (ESCR = 0), the algorithm proceeds to the last procedure, which is the grid storage operation.

The GD signal is responsible for reporting the demand for energy from the distribution network. If it is met (GD = 1), the algorithm performs this procedure. If not (GD = 0), the algorithm returns to the "start" point and starts all the work from the beginning.

All the possible configurations of signals are shown in the full algorithm flowchart in Fig. 8, which thoroughly explains the specific procedures and the decided states. The proposed energy management algorithm for the advanced charging station ensures safe operation of the station, supports a number of modes, and allows for the inclusion of energy cost optimization methods, as the energy can be drawn from either the grid, integrated battery storage, or PV.

Thus, Task T1.2, "Development of the algorithm for the power flow controller (PFLC)," is completed.

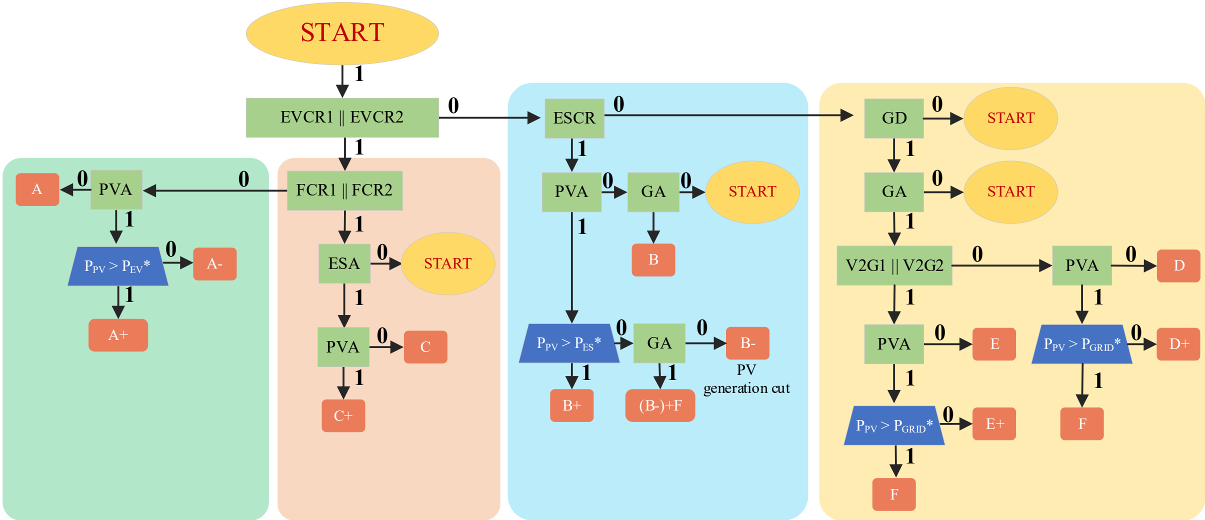

Fig. 8 Full flowchart of the energy management algorithm.

4 Conclusion

In the presented report, all the assumed works have been completed (T1.1 and T1.2). The proposed energy management algorithm for an advanced EV fast charging station with extra battery energy storage and PV integration is exhibited. All possible operating states of the system have been analyzed. The proposed power flow controller based on a flowchart-based algorithm ensures safe operation of the station, supports a vast array of modes, and enables the inclusion of energy cost optimization via sourcing the energy from either the grid, integrated battery storage, or PV.