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Enhanced Power Regulation in Multi-Port EV Fast Charging Systems Using FOPID-Based Adaptive Control

P. Chandra Babu[1], *Golla* Naresh Kumar[1], *Artham* Murali[1*], *Banothu* Ravindhar[1], and *Suresh Kumar* Sudabattula[2]

[1]B V Raju Institute of Technology, Narsapur, Telangana, 502313, India
[2]Lovely Professional University, Phagwara, Punjab, 144411, India

Abstract. The fast adoption of electric vehicles (EVs) has basically forced the need for a modern, dependable, and extremely fast charging network. Consequently, this study presents an Adaptive Energy Management Technique (AEMT) with a Fractional-Order PID (FOPID) controller for multi-port fast EV charging stations. The technique actively adjusts power sharing among EVs connected to the same charger, thereby enhancing energy utilization, reducing charging time, and ensuring that users receive an equal share of available resources. Due to its fractional-order nature, the FOPID controller offers greater flexibility and robustness when handling nonlinear operating conditions, grid disturbances, and varying charging demands of EV batteries compared to a standard PID controller. The proposed controller, makes the system capable of handling changes in demand and supply in an efficient way of power sharing among the ports. This provides a smooth CC-CV transition at 80% of SOC. The simulation results reveal that the FOPID controller is more efficient, as it can reduce the maximum load, and it is able to enhance the overall charging experience, as compared to the conventional method. The simulation is carried out in MATLAB/Simulink R2023b-Fixed-step discrete solver model.

1 Introduction

Electric vehicles have been a promising trend in the transportation industry around the world, but the time it takes to charge them is a common ongoing problem, needs to be addressed. Concerns about potential long charging times for EV's are certainly going to slow the adoption of this technology. Among the fast chargers for EVs, that is the group of devices which allows the shortest charging time, a couple of problems such as their limited geographic distribution, low operating time, and the interaction with the electrical network, have been identified [1-2]. These problems, therefore, have brought a lot of attention and appeal to researchers to move the next step of electrically driven vehicles further. Some researchers have concentrated on FEVCs localization to enhance local access significantly [3-4], while different sets of scholars have considered cost-cutting strategies and impact mitigation measures to uplift the scale of technological breakthroughs in the sector, to increase deployment readiness, to raise the rocket's reliability level, and to deepen their

*Corresponding author: murali.a@bvrit.ac.in

understanding of the physics of power electronic systems [5-8]. Furthermore, the challenge of enormous disparities in EV charging power requirements remains. While a standard-sized EV would be sufficient with 70-350 kWh such as MG ZS EV, Mahindra BE6, the Propel EV Dumper, Asok Leyland and Tesla Trucks, are medium and a heavy-duty EV (HDEV) may have an electricity consumption of up 20–300 kWh and up to 600 kWh respectively, with further prospects increasing up to 4.5 MWh. Therefore, most FEVC producers have chosen to use parallel power electronic modules (PEMs) to tackle this issue rather than a single module [9-10]. A PEM is normally in the range of 30–50 kW and consists of an AC–DC stage and a DC–DC stage [11]. With multiple PEMs, chargers will be able to switch on only those modules that are necessary to fulfil an EV's demand. To add even more versatility, multi-port chargers have been invented, which allow two EVs to be charged simultaneously but independently [12-13]. Each port, comprising several PEMs, is overseen by a respective charge controller that communicates with the EV via a power line communication (PLC) channel. To illustrate, if there are five 30 kW modules per port, and a Tata Nexon EV (45 kW) is connected to the first port, it required 2 ports, hence only two PEMs are active, and the remaining three are idle. Next, if a Tesla Model 3 (170 kW) is connected to the second port, the charger will not be able to deliver the full power request even though some of the PEMs in the first port are still unused. Thus, underutilization results in longer waiting or charging periods.

Solutions to these problems require more sophisticated energy management and power sharing mechanisms both at the charger and PEM levels. Whereas energy management strategies have been implemented in AC/DC micro grids [14], battery systems, and load scheduling frameworks, only a few works have directly focused on the coordination of PEM-level and charger-level operations in FEVCs. The present study closes this gap by developing an AEM and power-sharing scheme based on the proposed idea of PEM borrowing. This method permits the temporary reassignment of inactive PEMs from one port or charger to another, thus allowing medium-duty chargers to efficiently facilitate heavy-duty EVs without loss of charging speed or efficiency.

The main objective of the article is:

1. An innovative energy management system for the case of fast electric vehicle chargers at both power electronic module and charger levels. 2. Dedicating a communication protocol to the charge controllers that facilitates the negotiation process. 3. The introduction of a new concept of borrowing power electronic modules which may be applied either at the port or at the charger levels.

The paper introduces a Fractional Order PID (FOPID) controller as the core of the adaptive energy management system. The fractional-order design gives the controller more adaptability and strength than a traditional PID one, thus making it an appropriate tool for the nonlinear EV charging dynamics and grid disturbances. The FOPID-based algorithm facilitates the real-time allocation of power to different EVs, on condition that grid stability is maintained, load on the modules is evenly distributed, and the user is more comfortable.

2 Methodology

2.1 Power electronics modules and FEVC's structure

Fig. 1, illustrates a PEM circuit diagram, it has two converters that are connected in cascade, an ac–dc converter and a dc–dc converter. These converters can work in both directions, but because of the high cost, most of the FEVCs that are available only work in one direction. Every PEM has a communication bus with its own controller that gets the voltage and current reference signals.

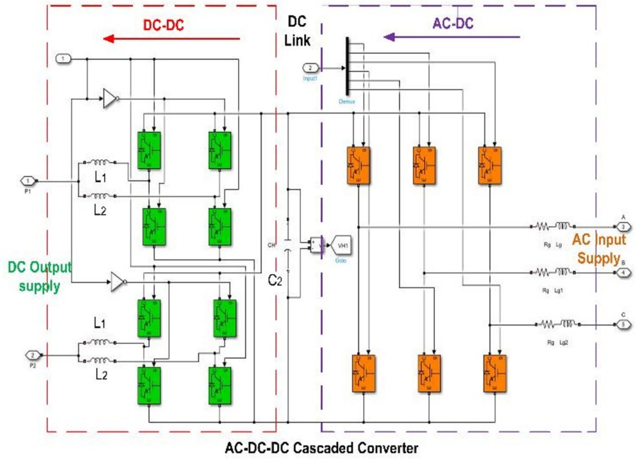


Fig. 1. Circuit diagram for PEM.

The control algorithm generates PWM signals from the received references. Multiple PEMs can be connected in parallel with a common AC input from the grid and a common DC output to the charging port; this is known as a multimodule rapid EV charger. Furthermore, each PEM has a contactor/relay at its output that connects and disconnects from the charging port. Similarly, two sets of parallel modules can be utilised to build a dual-port charger. To solve this problem, a communication bus is connected between the charge controllers of each port, based on CAN-Bus, as illustrated in Figure 2. A single CAN-Bus can be used to connect the PEMs to their charging controllers and the charging controllers to each other. There are separate switches that connect modules 1a-5a to charging port 1, and there are also separate switches that are usually open that connect them to charging port 2. When port Y borrows a PEM from port X, the reference signals for this module must come from the port Y charge controller. Because of this, X is in charge of moving these values from Y to borrowed modules.

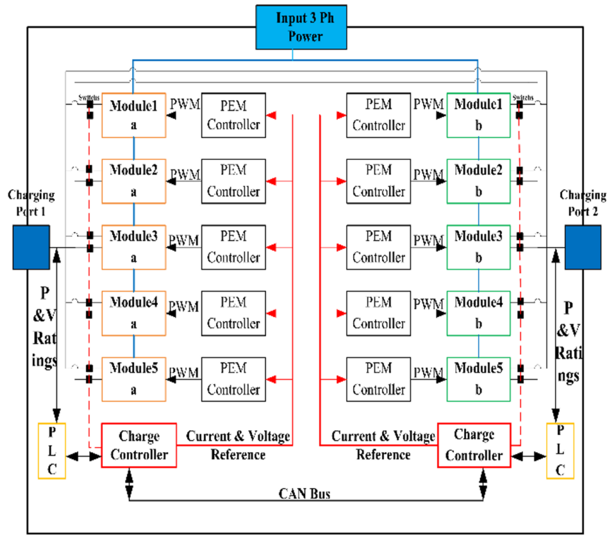


Fig. 2. Proposed dual-port fast EV charger structure.

2.2 Control technique for PEM level

There are two possible connections for ac–dc converters, a single ac–dc converter for each dc–dc converter, or multiple ac–dc converters connected in parallel to form a command clink that feeds all the dc–dc converters. In this study, three ac–dc converters are used to form a constant dc link voltage. In this case, the charge controller sends only the reference voltage signal (VH) for the formed dc link. One of the rectifiers will work as a master, while the others will act as slaves. Usually, the ac–dc converter works as boosting active front-end rectifier, which means that its output voltage is always higher than the input and charging port voltages. Therefore, in this study, it is called VH, while its current is called IH. Similarly, the terms V_L and I_L are used for the charging port's voltage and current, respectively. The dynamic model of a three-phase AFR is given by equations 1 and 2 given below

$$V_{abc} = L_g \frac{dI_{abc}}{dt} + R_g I_{abc} + U_{abc} \quad (1)$$

$$C\frac{dV_H}{dt} = \frac{3}{2}\frac{V_d I_d + V_q I_q}{V_{dc}} - I_H \quad (2)$$

where L_g is the inductance of the input filter, V_{abc} is the grid voltage, I_{abc} is the grid current, R_g is the resistance of the input filter, U_{abc} is the pole voltage which represents the control signal, while V_d, V_q, I_d, and I_q are the grid voltages and currents represented in d_q frame. Equation (2) reveals that VH has no direct relation with the control signal U_{abc}, instead, it has a direct relation with I_{abc} and IH. As IH is a result of how much power will be consumed from the formed the dc link, it will change independently from the other states. As a result, to control the rectifier, two control loops are required, one to compute the reference ac required to regulate the voltage, and another loop to regulate the ac using the control signal U_{abc}. The, ac reference current can be described as follows:

$$I_d^*(V_e) = K_1(V_e) + K_2 \int (V_e)dt \quad (3)$$

where Id is the reference grid current, K_1 is the proportional gain, K_2 is the integral gain, and V_e is the error in the dc link voltage. In fact, equation (3) can be computed by one of the rectifiers which is considered the master and shares it with the other rectifiers that are considered slaves. When the reference ac signal is received from the master, the control signal for current regulation can be computed as follows:

$$U_{abci} = I_{abci} - I_{abci}^* \quad (4)$$

where,

$$I_{abci}^* = R_i I_d^* \left[cos\,(\omega t) \quad cos\,(\omega t + \frac{2\pi}{3}) \quad cos\,(\omega t - \frac{2\pi}{3})\right]^T \quad (5)$$

R_i is the power sharing ratio, and ωt is the phase angle. The adopted dc–dc converter can operate in two modes, namely battery to dc link and dc link to battery. In battery to dc link mode, the converter works as an interleaved boost converter that boosts the battery voltage and supports the dc link voltage. In the second mode, the converter works as an interleaved buck converter, which is the focus of this study, and its dynamic model equations are shown in equations 6 to 7.

$$\frac{dI_{Ly}}{dt} = \frac{1}{L_v}(U_y V_L - V_H - RI_{Ly}) \quad (6)$$

$$\frac{dV_L}{dt} = \frac{1}{C}(I_{Ly} - \frac{V_H}{R_L}) \quad (7)$$

The output current of the dc–dc converter can be regulated using SMC as follows:

$$U_{12} = \frac{1}{2} I_2 \times I_L^* - \begin{bmatrix} I_{L1} \\ I_{L2} \end{bmatrix} \quad (8)$$

3 Proposed FOPID controller

In the extension PI controller replaced by FOPID controller, the proposed system gives fast response and high accuracy. A standard FOPID controller can be mathematically represented through its transfer function as

$$C(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \quad (9)$$

Where:

- K_p: Proportional gain, K_i: Integral gain, K_d: Derivative gain
- λ: Order of integral ($0 < \lambda \leq 1$), μ: Order of derivative ($0 < \mu \leq 1$)

The parameters λ and μ serve as additional tuning factors that enable more precise adjustment of phase and gain margins, thereby improving system stability and widening the bandwidth. Adding a FOPID controller into the multiport electric vehicle charger results in the charger becoming more adaptable, stable, and capable of delivering power in all three modes. When a FOPID framework is used in place of the conventional controller, the system transforms from a straightforward power conversion device into an intelligent, adaptable, and grid-compliant energy distribution platform. The SOC estimated based on mathematical equation (10)

$$SoC(t) = SoC_0 + 1/C_{bat} \int i_L(t)dt \quad (10)$$

3.1 Case studies

3.3.1 Case study-1

In this case, it is assumed that a charger has two charging ports, with five-modules per port, as shown in Table I. Each module is 30kW, so in total 150kW is available per port. Nissan leaf requires 50kW and is connected to port 1. Tesla Model 3 requires 170kW (Model 3 Rear-Wheel Drive) and is connected to port 2. In conventional chargers, port 2 can provide only 150kW. However, when the proposed PEM borrowing technique is adopted, port 1 will use only two PEMs and the three other modules remain idle. Therefore, when port 2 sends a borrowing request, port 1 will approve and assign one PEM to port 2 as shown in Fig.3.In this case, port 1 will use two modules, assign one PEM to port 2, and has two idle PEMs. On the other hand, port 2 has six PEMs with total power of 180kW. As a result, both ports can charge the connected EVs at their nominal charge power.

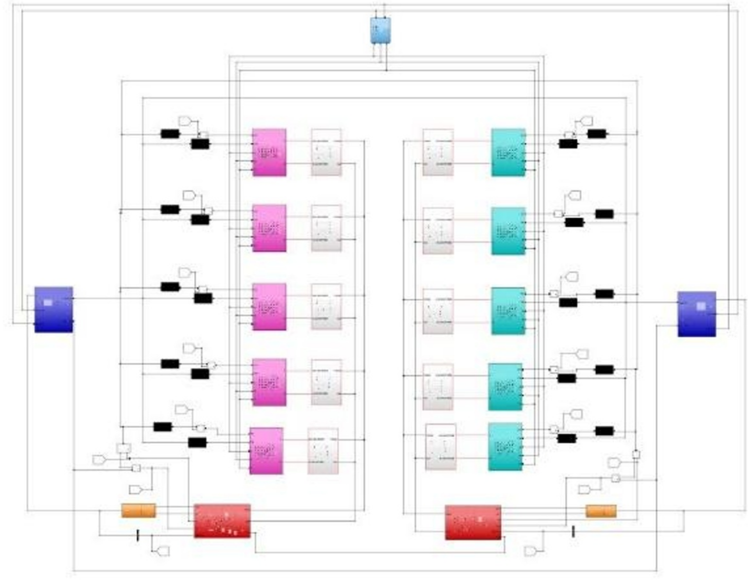


Fig. 3. Casestudy1: port2 is borrowing one PEM from port 1.

Table 1. List of components, parameters, and ratings for simulation case studies.

Parameter	EV1 (CS1)	EV2 (CS1)	EV3 (CS2)	EV4 (CS2)
Ratings	50 kW	170 kW	50 kW	250 kW
Main Port	Port 1, Unit 1	Port 2, Unit 1	Port 1, Unit 2	Port 2, Unit 2
Nominal Voltage	400 V	400 V	400 V	400 V
Initial SoC	50%	50%	50%	50%
Number of Idle PEMs	3	-	3	-
Number of Borrowed PEMs	-	1	-	4

3.1.2 Case study-2

In this case, Nissan leaf (50kW) is connected to port 1 of another charger, so two PEM are required for port 1, and three modules remain idle. Tesla Model 3 Long Range and Performance (LARP) requires 250kW, so nine modules are required. In this case the charging station cannot charge both EVs at the same time with their nominal power which will increase the charging time. However, the proposed solution can solve this problem as follows:

1) First, feed the lower power EV and determine the number of idle modules.
2) Compute the total available power in this station based on the idle modules from port 2.
3) Request to borrow all idle PEMs from port 1.
4) If the total available power is still insufficient after borrowing, request borrowing from other charging units. Assuming that another charging unit is operating under the conditions shown in case 1, which has two idle modules. Therefore, unit 1 can assign two PEMs to unit 2 as shown in Fig.4. The first unit can fulfill charging requirements as explained in case 1, and assigns two PEMs to port 2 of unit 2. Port 2 of unit 2 has five original PEMs, three borrowed from port 1 of unit 2, and one borrowed from unit 1 port 1. This means there are nine PEMs feeding port 2 of unit 2. Therefore, this port can provide 270kW and can easily fulfill the charging power requirements of Tesla Model 3 LARP.

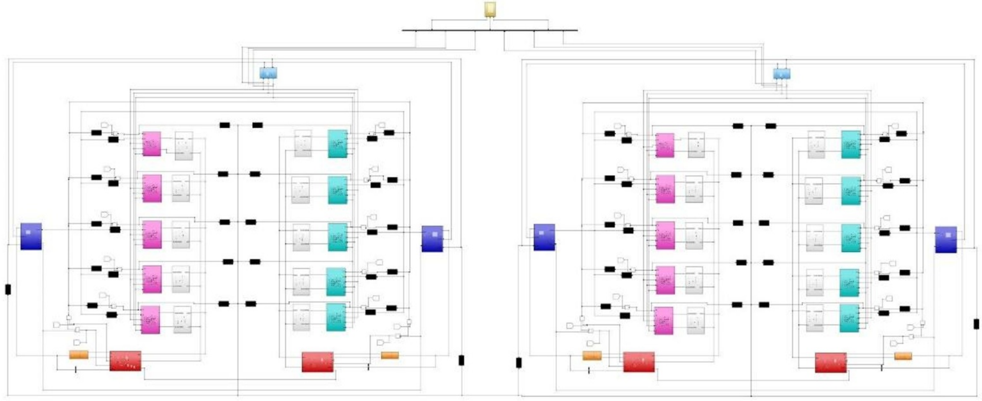
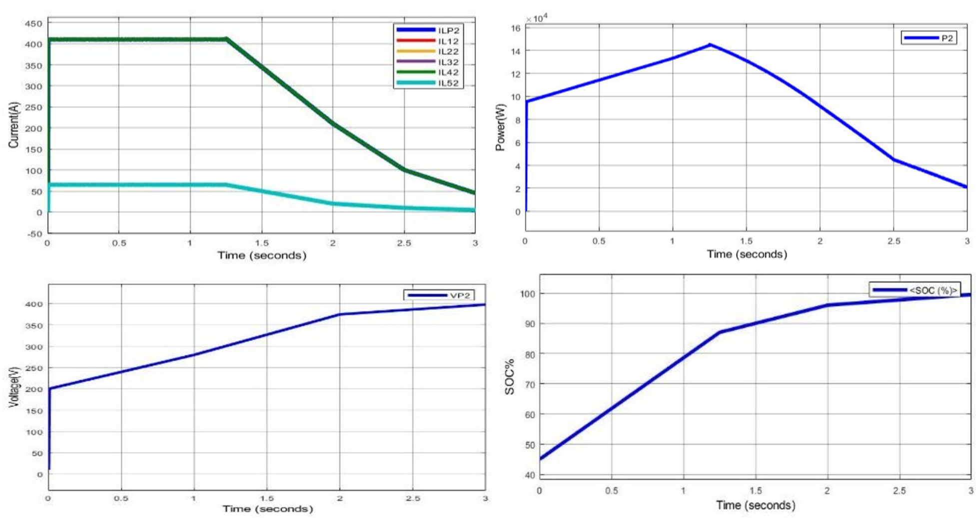


Fig. 4. Case study2: PEMs borrowing between different charging units.

4 Results and discussion

4.1 Without FOPID controller

The simulation results are demonstrated for case study 1 and 2. The simulation environment adopted here is in MATLAB/Simulink 2023b, Fixed-step discrete solver with sampling time of Ts = 1 μs. The first case study represents the charging process of 50kW and 170kW EVs connected to port 1 and 2, respectively. The nominal voltage is 400V, the initial voltage is 200V, and the initial SoC for each EV is assumed as 50%to reduce the simulation time. Based on (9), the reference CCs are 62.5A for the contributing PEMs in port1(PEM11 and PEM21) and 70.8A for the contributing PEMs (PEM12–PEM52) in port 2 and the borrowed PEM from port1(PEM51). Fig. 5 shows the response of port 1 modules' currents, powers, SoCs, and charging voltages, where I_{Li} is the dc through the i_{th} charging port, I_{Li} is the current of the i_{th} PEM module, P is the dc power of the charging port, SoC is the state of charge of the connected EV's battery, and V_L is the output voltage of the charging port. It can be noticed that PEM11 and PEM21 are sharing the power equally and follow the charging profile of the first charging port, PEM31 and PEM41 are idle, and PEM51 is following the charging profile of port 2. This means that PEM51 is borrowed by the second port and its charging controller is indirectly controlling PEM51 response. Moreover, it can be noticed that the charging mode is switched from CC to CV accurately and smoothly at 80% SoC, which is one of the objectives of this study. Similarly, charging port 2 fulfils the charging requirements and successfully borrowed one PEM from port 2. Fig. 6 shows the response of the second charging port PEMs. The total current through the second charging port represents the sum of all port 2 PEMs' currents in addition to the currents of the PEMs borrowed from the first port. As all PEMs are sharing the power equally, all currents are equal and are completely aligned to each other. In case 2, an additional two-ports charging module is added to the system. 50kW EV is connected to port 1 and 250kW, 400V EV is connected to port 2. In total, port 2 now has 9 PEMs, and the reference charging CC is 62.5A. Therefore, each PEM shares 69.4A to fulfil charging power requirement. This case shows that the first port can share power with other ports and other charging units effectively without affecting its normal operation or the speed of the charging process.



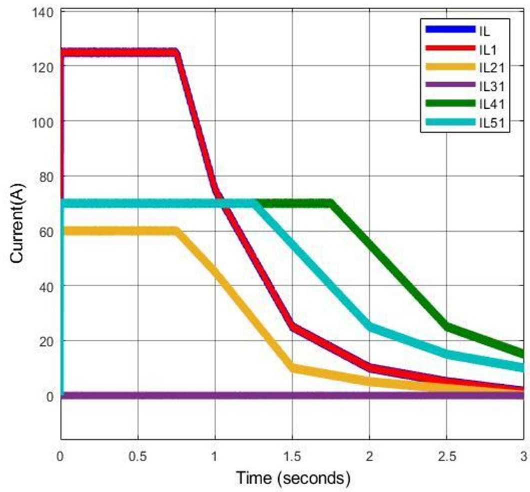


Fig. 5. Case 1: Current, Charging Voltage, Power, SoC of Port 2 and Response of charging unit 1 port1.

4.2 With FOPID controller

This part discusses about using simulations to evaluate two case studies for a multi-port rapid charging system for electric vehicles shown in Fig 6. A FOPID-driven energy management system is added to both case studies. It dynamically controls the Power Electronic Module (PEM) engagement across numerous ports and units, optimising the charging behaviour based on inputs including state SoC, voltage, and power demand.

Case Study 1: Two-Port Charging with Module Borrowing

- Two EVs are connected: a 50 kW vehicle to Port 1 and a 170 kW vehicle to Port 2.
- System starts with 200V initial voltage and 50% SoC for each EV; nominal voltage is 400V
- Calculated constant current (CC) values:
  - Port 1: 62.5 A (handled by PEM1a and PEM2a)
  - Port 2: 70.8 A (managed by PEM1b to PEM5b and borrowed PEM5a from Port 1)
- PEM31 and PEM41 remain inactive in this scenario

4.2.1 Role of FOPID-Based Controller:

- The FOPID adaptively assigns PEM5a to Port 2 by looking at the voltage and load conditions in real time. This makes it more efficient than fixed logic-based borrowing. The FOPID can tell when to move from constant current (CC) mode to constant voltage (CV) mode by constantly monitoring the SoC. This usually happens when the SoC is about 80%, but it might now be optimized based on learnt charging patterns.

Case Study 2: Multi-Unit Inter-Port Energy Allocation

- A 50 kW EV is connected to Port 1, while a 250 kW EV is connected to Port 2 in a system expanded with an additional charging unit
- Port 2 requires more power and therefore borrows:

Three PEMs from its local Port 1 and One PEM from Port 1 of the added charging unit

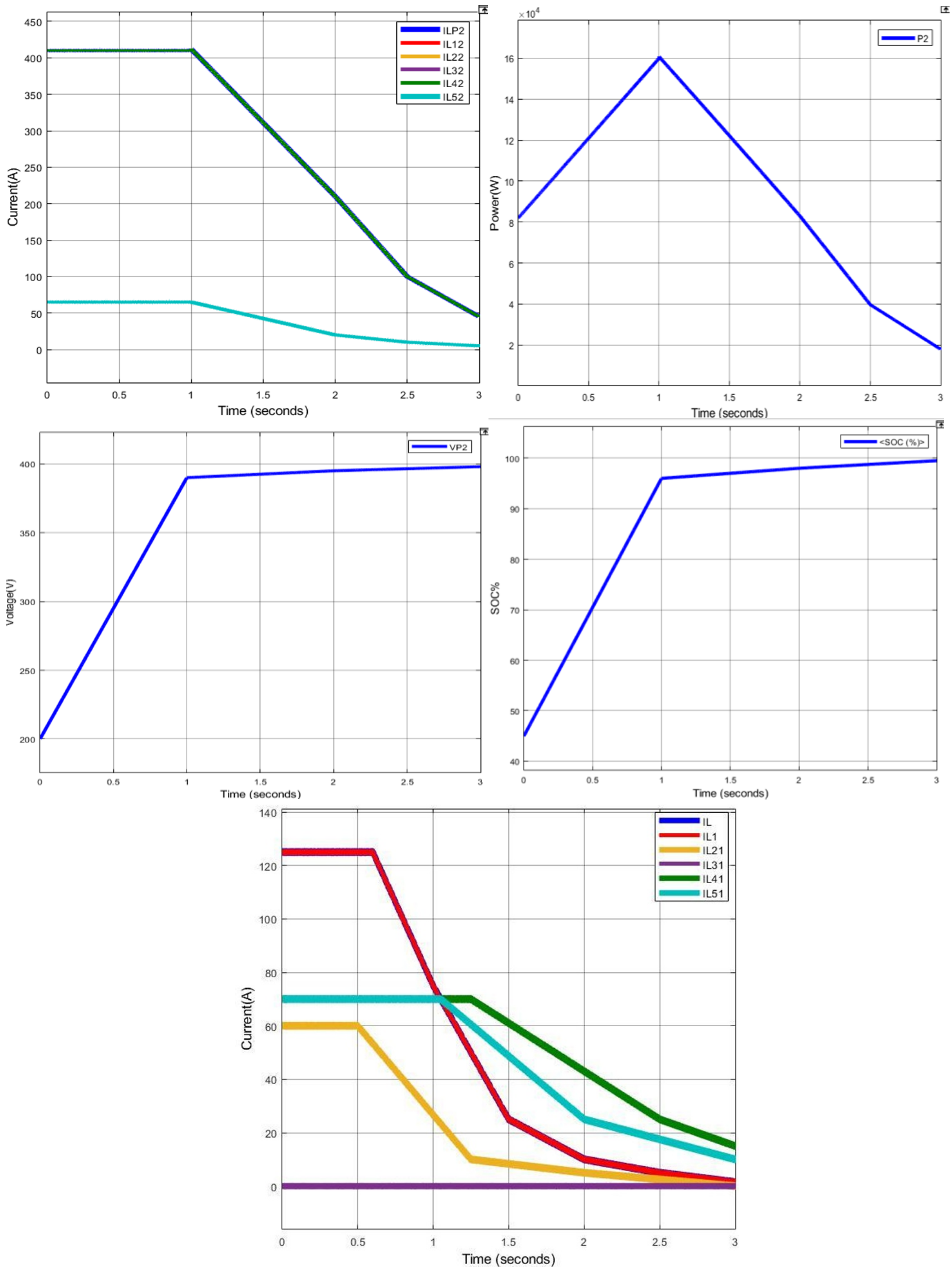


Fig. 6. Case 2: Current, Charging Voltage, Power, SoC of Port 2, The response of charging unit 1 port1.

With 9 active PEMs, each contributes approximately 69.4 A to meet the demand, FOPID-based Coordination provides seamless control profile switching for borrowed modules. As an illustration, a module that was once allocated to Port 1 is now able to reply to the controller of Port 2 without experiencing any delay or conflict. While the first and second modules continue to function in the same manner as before, the fourth PEM on Port 1 of Charging Unit 1 dynamically aligns itself with a new control signal that is issued by the next unit. The FOPID ensures that borrowed modules do not impact the performance of their source ports, thus maintaining charging speed and power balance. This represents real-time coordination between different units without causing disruptions to the local charging process.

5 Conclusion

This research work introduces an adaptive energy management approach that makes use of a FOPID controller to support the optimal functioning of multi-port fast-charging stations for EV's. The proposed approach, with the fractional-order control, can handle the different requirements for charging, distribute the power to the different charging ports, and even react to the changes both in the grid conditions and in the state of the vehicle. Simulation results provide evidence that the proposed control scheme is far beyond the traditional static allocation methods in terms of offering the possibility of real-time, adaptive regulation. As a result, the system can provide users with faster and more balanced charging sessions while at the same time maintaining grid stability and enabling the integration of renewable energy sources. The simulation results show the effectiveness of the proposed model in multi-port fast-charging architecture under different loading conditions. The accurate CC–CV transitions at 80% SoC, maintain equal current sharing among active PEMs.

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