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Integrated control and monitoring of a smart charging station with a proposed data exchange protocol

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Abstract

Expansion of electric vehicles' (EVs') charging stations is an unavoidable requirement in sustainable cities. Provision of safe protection and control infrastructure is one of the most important requirements for a reliable charging station. In this direction, a centralized protection, control and monitoring unit (PCMU) for smart charging stations is proposed here. PCMU communicates with chargers of the station, protective devices (e.g. relays and circuit breakers), local generating units and all other devices installed at the charging station to determine the station status and to detect/locate faults that may occur in the supply grid of the station. The PCMU includes a self-healing technique which is one of the specialties of smart systems that assists network reliability to increase. One of the major contributions of this research is to propose a protocol for data exchange between the PCMU and the other components similar to the logic used in standard of IEC 61850. Also, potential impacts of implementation of the proposed unit on the most-widely used reliability indices are discussed. The proposed protection strategy is examined via two case studies.

1 | INTRODUCTION

1.1 | Motivation, background, and literature review

Global warming and climate change, which are mainly linked to high consumption rate of fossil fuels, are the major challenges of future energy systems. Drawing attention to emission reduction in transportation sector is one of the most important sustainable solution to battle global warming [1]. To this purpose, considerable efforts have been put into development of pollution-free transportation technologies [2]. Introduction of electric vehicles (EVs) is an interesting solution to impact transportation sector's share of emission [3, 4]. In this regard, the associated technologies and their public acceptance are rapidly increasing throughout the world. EVs provide this capability to reduce air pollution and greenhouse gas emissions. This results in positive impacts on climate change, and oil use reduction in the transport sector. On the other hand, in the electricity sector, the potential of using EVs for grid service is increasing.

It is anticipated that the expanding EVs will pose a major charging load to the electricity infrastructure [5]. EV battery charging is a critical issue. In order to charge EVs, the so-called battery-swap stations can be deployed. In these stations, the discharged battery is replaced by a fully charged one. Compatibility of different EV battery types and the availability of charged batteries in the station are two issues that need to be considered. Converting power from the grid from AC to DC and using it for recharging the battery inside the EV is performed both in AC and DC charging styles. For Hybrid EVs (HEV) and Plug-in hybrid EVs (PHEV), the EV battery is typically a few kWh and for a PEV is tens of kWh. A few examples for HEV, PHEV, and PEV types are Toyota Prius with 1.3 kWh battery, BMW i8 PHEV with 7.1 kWh battery, and Tesla Model S with 85 kWh battery, respectively [6].

EVs can be charged either at home, or at public facilities such as parking lots or charging stations [7]. Charging the EVs at public facilities brings several advantages over home-based charging including, but not limited to charging management programs can be implemented more efficiently if EVs are aggregated in the same physical location. As a result, the imposed stress on the grid can be greatly alleviated [8]. Energy storage systems (ESSs) and renewable energy resources (RESs) can be integrated in the charging station to enhance the energy efficiency, and improve the reliability of supply to EVs [9]. Establishment of fast charging infrastructure can be more cost-effective compared to home-based charging. Moreover, total grid reinforcement costs for accommodating the required power could be reduced due to aggregation [10]. Procurement of ancillary services from vehicle-to-grid (V2G) programs such as reactive power compensation [11], emergency power supply [12], and peak load shaving [13] can be better aggregated in the charging stations. This causes savings in the required investments for electrical and data communication infrastructures.

Despite the mentioned advantages, a set of challenges have been addressed in the recent literature about the operational mechanisms of charging stations [14]. Some of the most important issues and the methods presented to solve them are explained here.

Optimal operation of the charging stations, market participation and pricing strategies, as well as stability of the station's supply grid are of the most important challenges in the operation of the charging stations. These challenges can be overcome by the use of the communication-based methods as are used in smart grids [15, 16]. The communication-based methods typically use real-time data to provide flexible and adaptive strategies. For instants, a real-time price-based charging strategy is proposed for charging stations [17]. In [18], a predictive model is proposed to predict EVs power demand and to provide a high level of accuracy and stability of the charging station by use of a real-time monitoring of each part of the station. In [19] photovoltaic (PV) units are integrated in the charging station and a dynamic linear programming (DLP) model is used for the optimization. A hybrid optimization scheme is introduced in [14] for minimizing the operating costs of an EV charging station integrated with PV and ESS. Also, in [14] a Real-time electricity price, real-time PV power production and degradation costs of ESS are incorporated in the optimization model. An optimal pricing scheme is proposed in [20], in which EV owners are assumed to be price-sensitive, and the number of EVs that leave the charging station without being charged is minimized. A stochastic linear programming model for optimal operation of a system of PHEV charging stations is proposed in [21]. The objective function is to maximize total profit, and wind as well as solar energy production are also considered. Authors of [22] proposed a convex model for optimal scheduling of EV charging stations, where total charging cost and the cost of energy imported from the grid are minimized. Based on above literature review, real-time monitoring and communication-based methods have been suggested to be used for various purposes in charging stations and create the concept of "smart charging stations"[15, 16].

On the other hand, some recent researches have been focused on optimal planning issues and challenges related to the placement of charging stations. For example a multiple-charger multiple-port charging system for charging stations is introduced in [23] and a two-stage stochastic programming model is proposed for planning of the station. Authors of [24] proposed a single-output multiple-cable charging spot, and developed a two-stage stochastic programming model for planning a public charging station integrated with such spots. A bi-level optimization model for placement of charging stations is presented in [25], in which travel cost of EV users to access the charging station as well as queuing cost in charging stations are considered. Moreover, the competitive behaviour of EV users are taken into account. Coordinated planning of charging stations and electric distribution system is another interesting topic, which is addressed in some recent researches such as [26, 27]. Coulomb Inc. invented a network-controlled charging system through a remote server. However, these stations are not appropriate for current sharing purposes, since they only have one or two outlets [28].

The above mentioned methods for the planning, coordination of stations and distribution systems and also methods presented to overcome issues about the participations of charging stations in the competitive marks, can provide better performance if they can receive real-time data from the all participants of the charging stations' market. Accordingly, the smart charging stations need to be equipped with adequate communication infrastructure as well as well-designed data transferring protocols. However, a comprehensive standard protocol, which can be used for various operational aspects of the smart stations, are not presented yet.

Another issue in implementation of charging station is selection a suitable and efficient system for their supply grid. Both AC and DC systems were suggested in previous work as the supply grid of charging stations. However, due to the advantages of new emerging DC distribution systems over the AC counterparts [29], especially in the grids that include many converters, DC systems were introduced as the supply grid of charging stations [16, 30, 31]. DC systems are also used to facilitate the integration of RESs to the station's supply grids, which can provide clean sources for the smart stations [32, 33]. The integration of RESs and other types of DGs, moreover, provide the possibility of implementation of network restoration systems which can enhance the reliability of charging stations. For these reasons DC supply grid has been selected for the study grid in this paper.

On the other hand, a careful literature reveals that although operational and planning aspects of charging stations as well as design of smart charging and energy management approach for EVs [34–36] have gained significant attention from the researchers in recent years, there are just a few papers, which addressed protection, fault management and network restoration in the smart stations.

In [29], various types of faults that may occur in DC supply grid of smart stations are introduced. Moreover, a protection scheme based on the use of overcurrent and under-voltage relays was proposed in [29]. A fault diagnosis method for DC smart stations, was presented in [31], in which the actual measurement data of the charging points are fed to a deep belief network that has been trained to detect the DC faults. This method, however, similar to other artificial-neural-network-based methods, needs an offline training process with the historical data, and is not easy to implement it for many stations. Moreover, charging stations not only may be fed by the utility grid, they can also be supplied by renewable energy sources or other types of distributed generation (DG) and energy storage systems; therefore, they can be effectively considered as microgrids and should be equipped with adaptive protection methods. However, the methods which are based on the conventional protection methods, are not designed based on the requirements of the supply grids of the smarts stations that may include renewable energy resources. In addition, due to the difference between the behaviour of fault current in AC and DC system, AC breakers cannot provide adequate protection for DC systems. Therefore, an [37] an electronic switch is presented for DC charging stations which is fast enough to clear the DC faults, with high rising rate currents, and preserve the stations' components and EVs supplied from the station's grid. The electronic-based DC circuit breakers, however, are expensive devices and hence in many smart stations it is not economic to use these CBs at all the feeder of the supply grid.

In addition to the protection issues, fault management and network restoration is another issue that should be considered in the designing of the control units of the smart stations. By use of an adequate and smart network restoration, the station gets back to normal operation with minimum possible delay. However, not many published works have paid attention to network restoration in smart station. In the method presented in [38], after the overcurrent or ground fault detection, the related charging points (CPs) are de-energized. Then, after the fault clearance, the de-energized CPs are energized by receiving an authorized message, which is transmitted remotely. By this message, the CP starts its normal operation, automatically (without a manual reset) and the supply grid is restored. This method, moreover, cannot provide an effective and adaptive network restoration process to restore the smart station's grid and change the operation points of DGs and protection units after the fault occurrence inside the local grid or at the utility grid. While, to enhance the reliability of the smart charging stations and guarantee their continuous and stable operation, it is necessary to equip them with effective and smart fault management and network restoration systems.

Based on the above explanations, in order to facilitate the participation of smart stations to the charging-station-markets, it is necessary to not only collect the required information from the chargers of the station, but also design a suitable fault detection and fault management strategy to restore the station after a fault occurrence in the power grid of the station or chargers. Therefore, this paper, proposes a centralized protection, control and monitoring unit (PCMU) for smart charging stations to improve the supply reliability after the fault occurrence in the supply grid of a the smart station. The main goal of this paper is to facilitate the use of EVs by improving the reliability of charging stations and increasing the possibility of integration of RESs to the supply grids of stations. It is clear that a smart station with higher level of reliability as well as RES integration, may gain more success in the competitive charging-markets.

1.2 | Contributions

As mentioned above, to enhance the reliability of smart stations, it is necessary to provide an adequate adaptive protection and fault management method for the supply grid of these stations. However, the existing protection methods, such as methods presented in [29, 31, 37], are not only able to provide an ad adaptive protection (that is needed for the grids that are fed by renewable energy resources), but also cannot restore the grid after a fault occurrence, effectively. To overcome these issues, this paper presents a communication-based protection and fault management method that is able to adapt relays' setting after a change in the network topology, RES' output power or disconnection/re-connection of the utility grid. The proposed method also equipped with a self-healing system that enhances the reliability of the charging stations by providing a fast and automatic network/service restoration. This automatic systems can provide a fast network restoration (i.e. less than 1 min) while in the conventional methods the network restoration time cannot be shorter than several minutes (even in small stations) which can dramatically enhance the reliability of smart stations.

Moreover, to implement the communication-based methods, it is necessary to transmit the required data according to a standard protocol. However, there is no specific standard for exchanging the required data that are needed for the network restoration and fault management in smart stations. Therefore, the paper presents a protocol for defining the required variables that are exchanged between the network components during the fault management and network restoration process. The paper also shows how this protocol can be used in a smart station that is fed by utility grid and renewable-based/ conventional DGs.

On the other hand, the reliability indices of the charging stations, after using protection and fault management methods, were not investigated in the previous paper. However, to show the importance of using such a smart and communication-based protection and network restoration methods, and also to show that the proposed method has an effective impact on the reliability of smart stations, a reliability evaluation framework was proposed in the paper. Such a method, however, was not presented in the above reviewed papers; therefore, this framework can be used by the researchers that are working on the protection, fault management and network restoration of smart station to evaluate the reliability of the stations after the implementation of their proposed methods. It is noted that, in spite of recent progress in the design of smart charging and energy management approach for EVs, to the best of authors' knowledge, none of the previously published papers, including the recent literature such as [39] and [40], consider reliability evaluation of their proposed procedure.

The key contributions of this paper can be summarized as:

- A centralized protection and control unit that has been proposed for DC microgrids in our previous work [41] is modified to be applied in smart charging stations. The protection units of the method, are adapted to the station's operational

TABLE 1 Feature comparison of protection schemes

Paper	Application of the protection, monitoring and control method	Data exchange protocol	Generation unit	Network restoration	Reliability analysis
[42]	Power grid	✓	✓	✗	✗
[43]	Microgrid	✗	✓	✗	✗
[40]	Emerging distribution system	✗	✓	✗	✗
[38]	EV networked charging station	✗	✗	✗	✗
[29]	EV charging station	✗	✗	✗	✗
[41]	MVDC microgrid	✗	✓	✓	✗
[44]	Microgrid	✓	✓	✗	✗
[45]	Smart grid	✓	✓	✓	✗
[46]	Microgrid	✗	✓	✓	✗
[47]	DC systems	✓	✓	✗	✗
[48]	DC grid	✗	✗	✗	✗
[49]	Smart Distribution Grid	✓	✗	✓	✗
[50]	Distribution network	✗	✗	✗	✓
This paper	EV charging station	✓	✓	✓	✓

conditions and provides and effective fault clearance by using the minimum number of DCCBs.

- The message between control and protection devices are transmitted based on a proposed protocol. All variables that are used to exchange data between the PCMU and station's components are in a standard form similar to IEC 61850 that can be considered as a base for developing a protocol for monitoring and control systems of smart charging stations.
- The impacts of implementing the proposed PCMU on the most-widely used reliability indices are discussed and a reliability evaluation framework based on Monte Carlo simulation is introduced. This framework can be used by the other researchers to evaluate their future fault management and network restoration methods too.

In Table 1, the main features of the presented monitoring, control and protection (in PCMU) and the other features of the paper are summarized in comparison to the other existing literature in the field of this paper, that is, the smart stations, distribution systems and microgrids, and DC systems.

The rest of the paper is organized as follows: A monitoring, operation, and control of EV charging station is presented in Section 2. The developed PCMU and its different components are introduced in Section 3. The impacts of implementation of the proposed unit on the most-widely used reliability indices are discussed in Section 6. The case studies are presented in Section 5. The paper is finally concluded in Section 6.

2 | MONITORING, OPERATION, AND CONTROL OF EV CHARGING STATION

Two types of charging styles that are used in EVs are AC and DC power. The main grid provides AC power; however, batteries, such as the one in EVs, can only store power as DC type. That is the reason that most electronic devices need a converter to connect to the main grid. Abundant DC fast chargers in public spaces—including new high-power models that can charge an EV in close to the time it takes to fill a gas tank—are necessary to accelerate the transition to low-emission transportation. Public agencies and utilities should prioritize investments in DC infrastructure that serves current and future EV models as alternative for AC charging grids. DC systems also facilitate the integration of RESs to the station's supply grids. In this regard, we design the PCMU for DC charging station. A schematic representation of DC versus AC charging-station is depicted below in Figure 1.

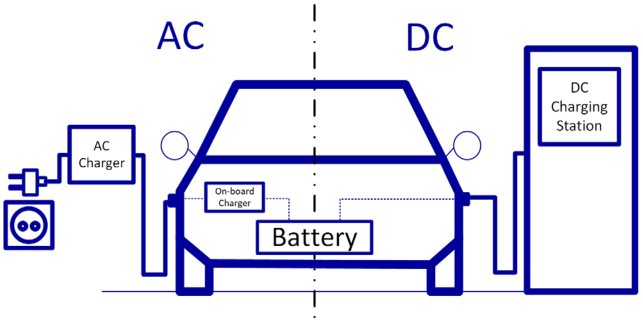

FIGURE 1 AC vs. DC charging station

The schematic model of EV charging station of the presented PCMU is shown in Figure 2. The proposed PCMU has two task levels: technical level (station level) and market level. The first level is within the scope of this paper. To perform the first task level, PCMU communicates with chargers of the station, protective devices (e.g. relays and circuit breakers), DG units and all other devices installed at the charging station to

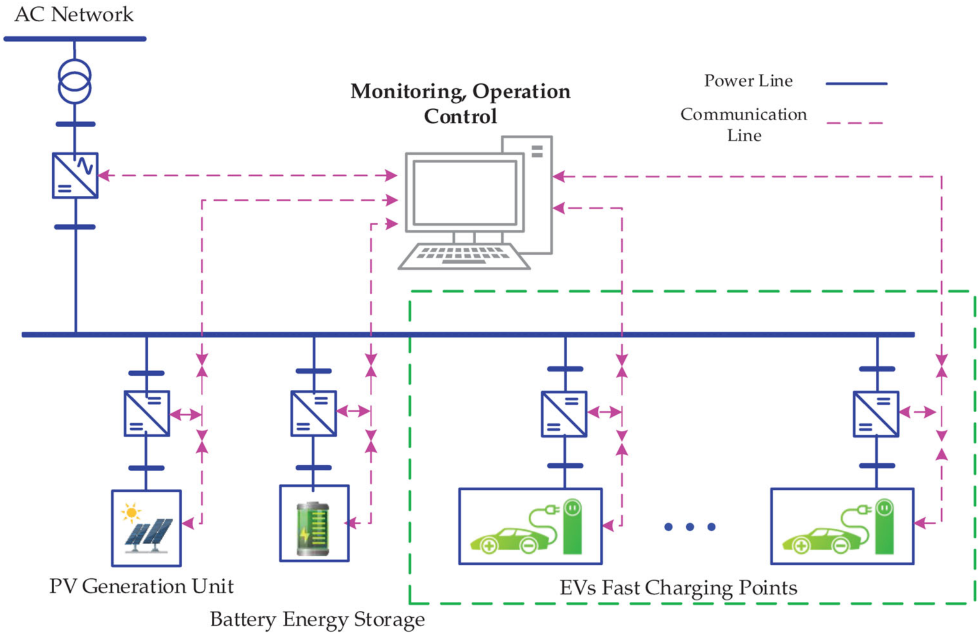

FIGURE 2 The structure of a centralized monitoring, operation and control unit for the smart charging stations

determine the station status and available charge. The PCMU also includes a self-healing algorithm; the self-healing is considered as one of the features of the smart grid that assists increasing the network reliability. To procure self-healing capabilities, distribution networks should be equipped with suitable control algorithms that enable them to automatically handle and address issues that occur during their normal operations. Therefore, a protection, control, and fault management unit is presented in this paper, which is included in an effective self-healing technique. This task level of PCMU also includes a power-source management unit that manages the utilization of local sources.

On the other hand, at the market level, PCMU should be able to communicate with consumers and other market participants to exchange information that is attractive from the perspective of the consumers. For example, by providing real-time, enough and useful information, the owners of the smart stations can maximize their consumers. Therefore, the PCMU reports the overall status of the stations to the EVs' owners. The last part of Table 2 shows that the PCMU shares these variables to the EVs: The spot charging price, the estimated time that each EV should be at the queue and the estimated charging time. To provide such information, the PCMU collects various types of data about the number of active CPs, the minimum price of other stations and other required information from its local monitoring system and wide area communication networks. Therefore, the PCMU will be equipped with adequate communication infrastructure (for both local and wide area data transferring) as well as analytical methods, and will operate according to standard protocols. The second task level of PCMU is out of the scope of this paper and can be developed in future research of the authors.

3 | THE PROPOSED PCMU

The proposed PCMU's performance is assessed, in the context of a typical smart station's supply grid, as depicted in Figure 3. It is noted that, in compare to the station of Figure 2, the station of Figure 3 is a larger charging station; however, there is no basic difference between the stations of these figures. Indeed, we have considered Figure 3 as our study grid because it is a larger grid and therefore more scenarios and case studies can be defined in it. This network's configuration and parameters are given from the previous research of the authors presented in [41]. The redesigned microgrid of [41] is adopted in this paper as the study grid for a charging station, as shown in Figure 3. The network is a DC system consisting of DGs which are interfaced to the grid through voltage source converters (VSCs), charging points (as loads) and DC feeders. Note that, each DG and its related converter are assumed as a unit, named as DG unit. Indeed, each DG unit is composed of a generator and its converter in which, all the converters are controlled by their inner controllers. All DGs have adequate inner controllers too. When the main control unit of the station needs to change the output power of a DG, it send the new setting to the DG unit. Then, the new set point is applied to the inner controller of the DG as well as the inner controller of the converter to change the output power. The operation of the inner controller of the DGs and their converter is not in the scope of this paper.

As mentioned above, smart stations can be fed by use of AC or DC feeder; however due to the advantages of new emerging DC distribution systems over the AC counterparts [51], especially in the grids that include many converters, a DC system has been selected for the study grid. The PCMU can be used in both AC and DC supply grids of smart stations.

TABLE 2 The values required by the PCMU (transmitted variables)

Input (to PCMU)			**Outputs (from PCMU)**		
Name	**Type**	**Description**	**Name**	**Type**	**Description**
Signal exchanged between PCMU and DGs.					
DgStat	Bool	The status of DG (connected or not).	DgOuPo	Float	The set point of the DG's output power.
DgGen	Float	Generated power of a DG.			
DgAvaPow	Float	Available power of a DG.			
DgTyp	Int.				
Signal exchanged between PCMU and isolator switches					
Stat	Bool	The isolator is working or is out of the service.	Opn	Bool	"Open" command to isolator.
			Cls	Bool	"Close" command to isolator.
Signal exchanged between PCMU and CBs					
Stat	Bool	The CB is working or is out of the service.	Trp	Bool	"Trip" command to CBs.
			Cls	Bool	"Close" command to CB.
Signal exchanged between PCMU and DG's relays (SPRs)					
Stat	Bool	The relay is working or is out of the service.	Set	Float	Set relay's setting.
			Trp	Bool	Activate the trip command remotely.
			Cls	Bool	Activate the close command from relay, remotely.
Signal exchanged between PCMU and charging points (CPs)					
Stat	Bool	Status of each charging point.	Opr	Bool	Change operation mode (Turn On or ff)
NoCaQ	Int.	Number of EVs in que.			
Pow	Float	The power consumption of the CP.			
Signal exchanged between PCMU and EVs (for the tasks defined in the second level of operation)					
Outputs			Inputs		
SptPri	Float	Spot charging price.	NoChPo	Int.	Number of active charging points.
QuTim	Float	Estimated time that each EV should be at the que (minute).	MinPri	Float	Minimum price other stations.
CharTim	Float	Estimated time that each EV is charged (related to the charger points' speed).			
Internal signal exchanged between the Units of the PCMU(in addition to above signals)					
From DPU to Control Unit					
FutDet	Bool	Fault detection by each protective relay.			
FutLoc	Int.	Determine the fault location to facilitate the grid restoration.			

One of the main roles of the PCMU is providing a smart protection and fault management strategy for the electrical grid of the smart stations. In fact, in order to guarantee continuous and safe operation of smart charging stations, their power grid should be protected by use of the adequate fault detection and fault clearance strategy. The selected protection strategy for the smart station is based on the method presented in [41] for smart DC distribution systems. The components of the protection system are briefly described in the following.

It is assumed that converters that are used to connect DGs and smart points to the station's grid, cannot block fault currents. Therefore, it is necessary to use the adequate DC circuit breakers (DCCBs) to interrupt the fault current and to protect the grid and its components. DCCBs, are more expensive than

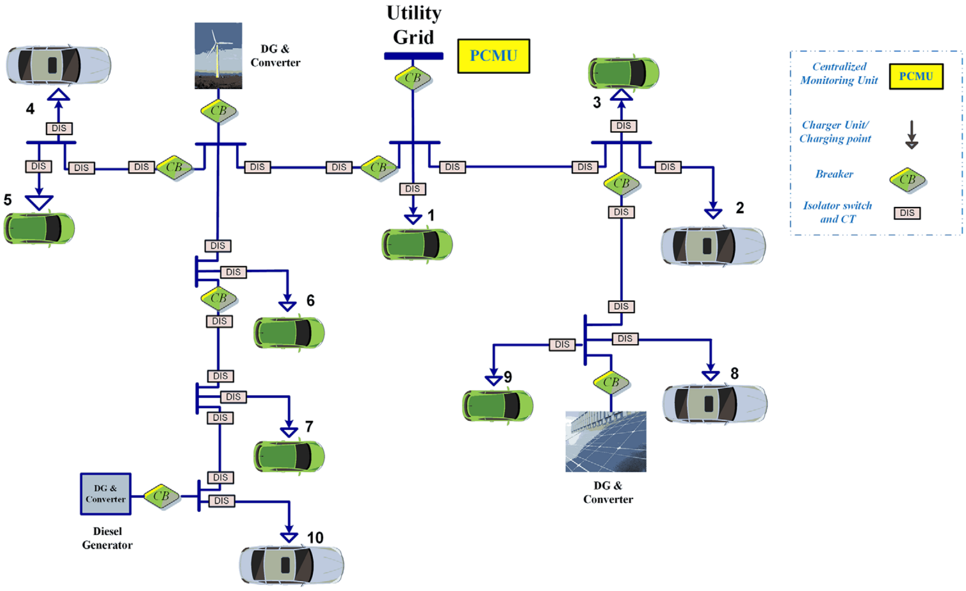

FIGURE 3 A typical smart station's supply grid

AC breakers; hence, the fault interrupting and isolation is provided by a combination of DCCBs and isolator switches. By use of this strategy, the minimum possible DCCBs are used. As explained in [41], in this method, the fault current is interrupted by use of DCCBs and the faulty line is isolated by opening the isolator switches located at both sides of the line. Therefore, after a fault occurrence, the faulty section is isolated and by use of a "cut and try" process the rest sections of the station is restored very fast.

On the other hand, the fault detection and location is handled by differential-based protection as well as overcurrent-based relays. Due to the high raising rate of the DC fault currents, it is not easy to coordinate overcurrent-based relays in these systems. Therefore, in the presented protection system, the fault is detected and located by use of the differential protection units. As it is shown in Figure 4, the PCMU includes differential protection unit (DPU) that consists of several differential-based (Diff) protection unit. Each line/ busbar of the station's grid is protected by a Diff unit. For this reason, it is necessary to provide a suitable communication link between current transformers (CTs) and the DPU of the PCMU. After a fault occurrence, the DPU send two variables to the control unit of the PCMU to report the fault occurrence and the location of the detected fault. As it is shown in Table 2, these two variables are named as "FutDet" and "FutLoc". All other variables that are used to exchange data between the PCMU and station's components are introduced in Table 2. It is noted that these variables are the variables that are required for PCMU to run its protection and fault management program. It is worth noting that, for other purposes, each component may send/ receive more standard variable to/ from other devices. Those variables, or variable similar to them, have normally been introduced by available standards, such as IEC61850, therefore are not reported in Table 2. It should be noted that, all the devices that would like to communicate with each other should work base on a similar protocol, otherwise each device needs a gateway to translate messages that are received from other devices that work based on another protocol. This gateway is a software that reads an incoming message which is published using the format of a protocol, named for example, A opens the message, puts the including data in a new message with the format of another protocol, for example named as B, and sends it to the other device. Therefore, if each of the installed devices in the station's grid, for example, CBs and CTs, works based on another protocol, a gateway is needed to work as an interface between that device and the PCMU.

Moreover, knowing that after the fault occurrence at any point of the station's grid, the fault current is supplied by the main grid and the DGs that are installed in the station, overcurrent-based (OC) relays, which are named as source protection relay (SPR) are located at the connection point of DGs and utility grid to the station's grid. Due to the high raising rate of the DC faults, these relays are able to detect the fault in less than several microseconds. The pickup current of SPRs is set according to the critical time of the related protected converter and the rated current of the related feeder. It is noted that the SPRs can also be removed and their protection task can be handled by the PCMU; however, to provide a redundant protection for the station sources, theses relays were considered as a part of the station's protection system too. The CBs can be opened/closed by a command from the PCMU or their local SPRs.

Figure 4 shows the main inner units of the PCMU, the required data that is collected from the station's components and the commands that are generated by the PCMU. Differential protection unit was explained above and is the main fault detection/location of the PCMU; this units protects all the feeders and buses of the station. DG unit, is a unit that communicate with DGs that are installed in the station. Each DG need

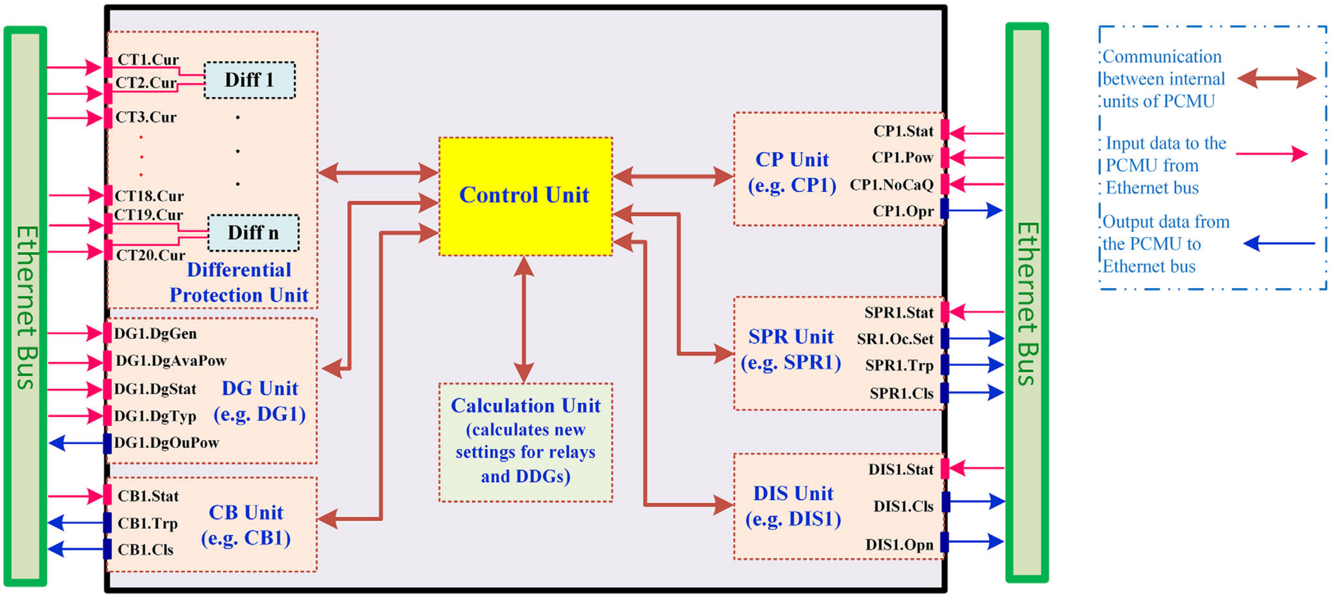

FIGURE 4 The structure of the proposed PCMU. The inner units and the required data for the PCMU installed in a typical smart station (only one communication unit for DGs, CBs, isolator switches, SPR relays, and CPs are shown)

an individual DG unit for itself. CB Unit, CP Unit, SPR Unit and DIS Units, are the units that are defined to exchange data with a circuit breaker, charging point, source relays, and isolator switches, respectively. By use of these units the required variables that are introduced in Table 2 are exchanged between PCMU and station's components. It is clear that the number of each unit is determined based on the number of the related component that was installed in the station. For instant, for the study station of Figure 3, three DG Units should be defined for the PCMU.

The PCMU also is equipped by a calculation unit: The main task of this unit is calculating the new operational setting of the stations components. For example, by knowing the status of CBs and isolator switches, the calculation unit determines the topology of the station's grid. After that, by using the real-time data about the generated power of each DG and required power of the CPs, the unit determines the new setting for the output power of the dispatchable DGs (DDGs). This unit is responsible of the calculation of relays' setting afar a change in grid's topology or sources outputs.

The control unit monitors the operation of all other units and coordinate them. All the variable are exchanged in the PCMU units through the control unit. Indeed, the control unit executes the proposed method and manages the data transferring between all other units of the PCMU. The main fault management and network restoration algorithm of the PCMU, which is handled by the control unit, is shown as a finite-state machine in Figure 5. Each states shown in Figure 5 defined for one of the various stages of the proposed method.

About the data transferring between the inner units of the PCMU and the devices that are installed in the station grid, two types of communication are needed. First, all the inner Units of the PCMU are connected to the control units. This connection is shown in Figure 4 by use of brown arrows. Indeed, the inner units use these links to communicate with each other through the control unit. Second, all the units of the PCMU should be connected to the corresponding devices that are installed in the station. Ethernet bus was used to establish this type of communication and data transferring. It is clear that, to establish this data communication, all the installed devices in the station (e.g. CBs, DGs, CTs etc.) should be connected to the Ethernet bus too. In Figure 4, the small red and blue arrows are used, respectively, to show which data is received and sent by each unit of the PCMU. For example, CB1 of the station grid that is connected to the Ethernet bus sends "CB1.stat" message to the CB Unit1 of the PCMU; the red arrow shows that this message is fed into the related unit. In addition, two blue arrows show that CB Uunit1 sends "CB1.Trp" and "CB1.Cls" messages to the Ethernet bus to be transferred to CB1 and change the operation of CB1.

4 | RELIABILITY EVALUATION OF THE DEVELOPED PCMU

As earlier mentioned, reliability improvement is one the main motivations for implementing the proposed "centralized protection, control and monitoring unit" in smart charging stations. In this regard, it is expected that effective deployment of the introduced unit, charging service interruptions for the EVs will be reduced. On this basis, reliability impacts of the proposed scheme as well as the general analysis method will be discussed in this section.

The most widely used reliability indices in distribution systems can be classified into two main groups: customer-oriented indices, and load/energy-oriented indices [52]. The most

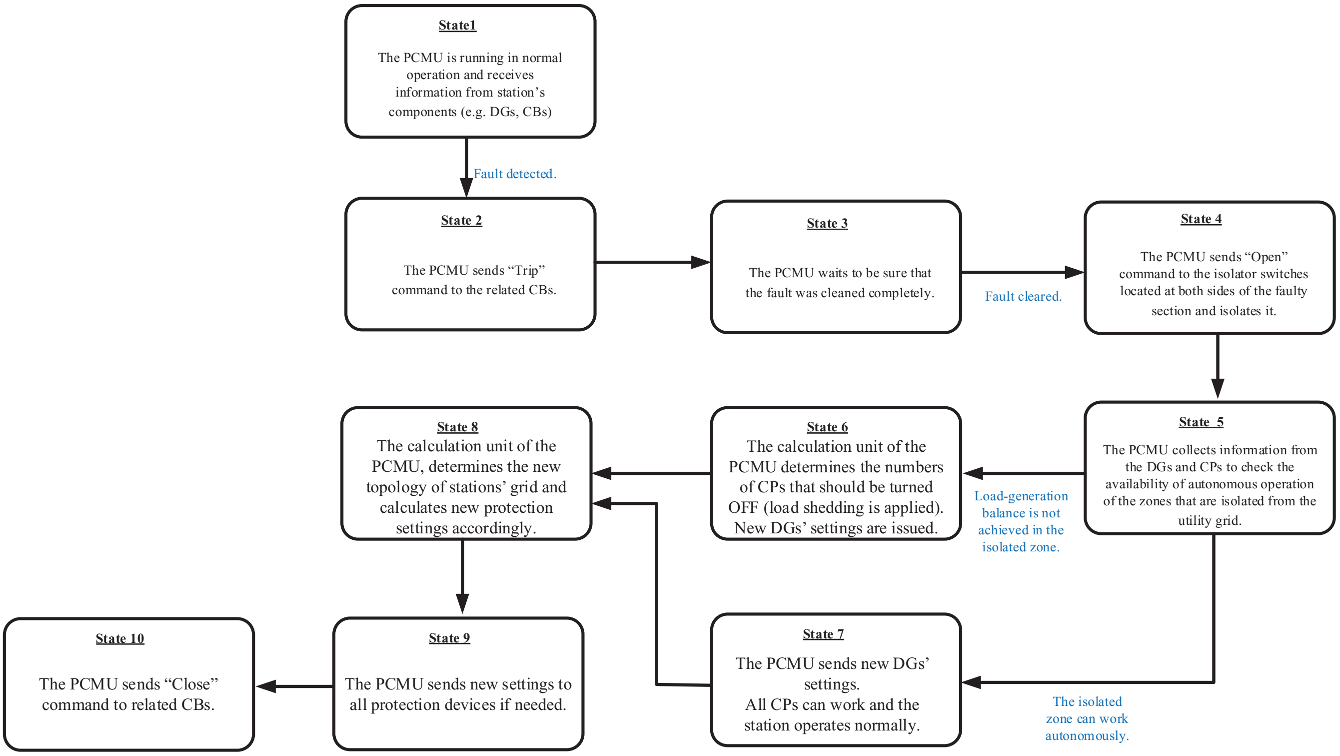

FIGURE 5 The protection, fault management and network reastoration algorithm of the PCMU

popular indices of first group are system average interruption frequency index (SAIFI), customer average interruption frequency index (CAIFI), system average interruption duration index (SAIDI), customer average interruption duration index (CAIDI), and average system availability/unavailability index (ASAI/ASUI). The energy not supplied (ENS) index, is the most popular index in the latter group. The definitions of these indices are completely addressed in [52, 53].

Successful implementation of the developed PCMU will affect the reliability performance of the charging station in two ways. Since effective adaptive protection is achieved with implementation of PCMU, protection system failures are reduced. These failures can be broadly classified under "mal-operation" and "failure to operate" categories [54]. Protection system reliability considerations usually address these two aspects as dependability and security [55]. Dependability is defined as the probability that the protection system will operate correctly. In other words, dependability is a measure of the protection system's ability to operate when required. On the other hand, security is defined as the probability that the protection system will not operate in those situations when tripping is not desired. As can be confirmed from the previous sections, deployment of the proposed system can reduce both types of protection system failures and as a result, charging points will experience less outage events.

On the other hand, with implementation of the proposed system, the restoration process would be more efficient once an outage occurs in the charging station/upstream grid. In this context, fault location algorithms will be conducted faster, and the associated switching times are reduced. Moreover, operating points of DERs are specified and conveyed to them more efficiently, and due to these facts, the islands will be established faster. It is also clear that, by use of this method, the restoration process failures will decrease. These facts reduce the outage times of the charging points and maximize the load that can be restored. In addition, due to the availability of real-time status of the connected EVs and since available power is likely to be inadequate to meet the total EVs' demand, it can be allocated to the connected EVs more effectively, based on their specifications/demands/priorities such as the charging power, state of charge (SOC)/required energy, expected departure times etc.

On these bases, it can be confirmed that all the above-mentioned reliability indices will be improved if the developed PCMU is implemented. In other words, less outage events would occur for the connected EVs and as a result, frequency-related indices such as SAIFI, and CAIFI will improve. On the other hand, the duration of interruption is decreased and the amount of unsupplied load/energy will also decline. As a result, the other indices (namely SAIDI, CAIDI, ASAI/ASUI, and ENS) will also improve. These facts are summarized in Table 3. The extent of improvement, however, depends on many factors.

TABLE 3 The Reliability indices affected by the PCMU

Reliability indices	SAIFI	CAIFI	SAIDI	CAIDI	ASAI	ASUI	ENS
Affected by PCMU	✓	✓	✓	✓	✓	✓	✓

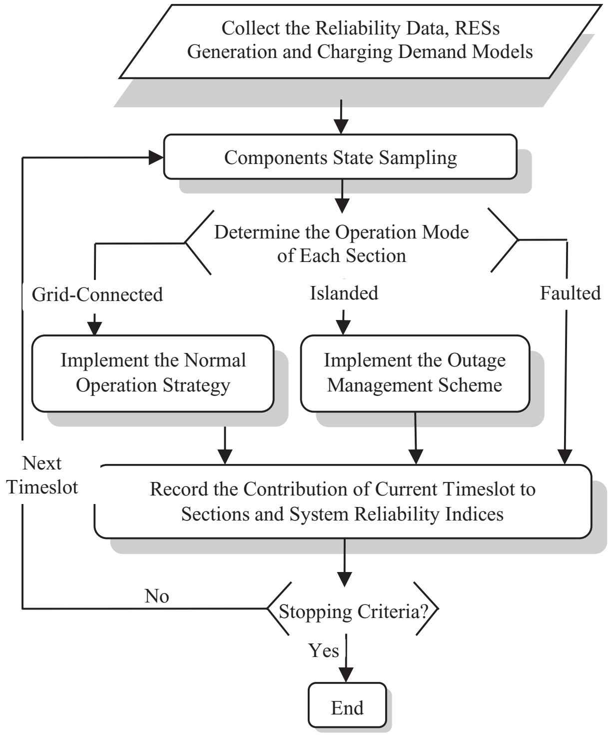

FIGURE 6 The proposed reliability evaluation framework

In order to evaluate the reliability indices of the charging station and assess the effectiveness of the introduced system, in the first step, the charging station should be divided into several smaller sections based on the configuration of the circuit breakers (CBs) [7,56]. Subsequently, the required data are collected. These include reliability data of components (mean-time-to-failure (MTTF) and repair (MTTR)), chronological data of load and renewable power generation. Moreover, probabilistic pattern of charging demand at different times should obtained from historical data or appropriate simulations [7]. In the next step, the operating mode of each section is determined at each simulation timeslot according to the status of upstream grid and also all the equipment located inside distribution network. Note that up/down status of different components at each timeslot are determined via random sampling method. Then, operational measures during normal as well as outage conditions are simulated and different reliability indices are calculated using Monte Carlo simulation method. This reliability evaluation framework is depicted in Figure 6. For further information about the operating modes of the sections within the charging station and charging management scheme, please refer to the authors' previous work [57]. It should be noted that since available power of DGs in islanded sections might be inadequate for meeting the entire demand, some priorities should be set for supplying different charging demands. These priorities have a major impact on the reliability of different charging points, and should be accurately addressed in the assessment of reliability indices. Detailed procedure of the reliability indices calculation and investigation of the main contributing factors, is beyond the scope of this paper and will be treated in a future work. However, an illustrative numerical example is provided in the next section to further highlight the impacts of the proposed scheme on the reliability indices.

5 | CASE STUDIES

In the following paragraphs, two fault scenarios are explained to demonstrate the effectiveness of the proposed method. In each scenario, the transmitted messages between the PCMU and other devices are determined. Moreover, the impacts of the proposed control and monitoring scheme on ENS index is explored via the third case study, and the results are compared with the conventional restoration mode.

The Matlab/Simulink environment was used to verify the proposed method. In this regard, the PCMU was simulated by use of the Stateflow chart of the Simulink. The Stateflow chart is a powerful devices that is used in the implementation and verification of the protection and control methods. All the states of the PCMU, which are defined in the Stateflow chart, were shown in Figure 5. Moreover, the study grid if Figure 7 was also simulated in the Matlab/Simulink and the required connections were established between the station grid's devices and the PCMU.

It should be noted that, in the following case studies, the operation of the PCMU as well as data transferring based on the proposed protocol were considered. Issues such as the latency in data transferring and data weight were not investigated here. Such considerations, that are needed to know the specifications of the protocol and its differences with the other ones, is the future work of this study. However, since the format of the protocol is similar to IEC61850, we think that its specifications should be almost similar to IEC61850.

5.1 | Case study 1: Fault F1 at line12

In the first case study it is assumed that a pole-to-pole (PP) fault occurs at the station's grid at the point labelled as F1 in Figure 7. The important messages generated by the PCMU, which are introduced in Table 2, are also reported. The applied scenario is as follows:

1. Fault occurs at point F1, at Line12.
2. CT12 and CT13 send currents to PCMU. Then PCMU detects the fault location that is at Line12.

$$FutLoc = '12'$$

$$FutDet = '1'$$

3. PMU sends trip command to CB7 and CB3 and they open.

$$CB7.Trp = '1'$$

$$CB3.Trp = '1'$$

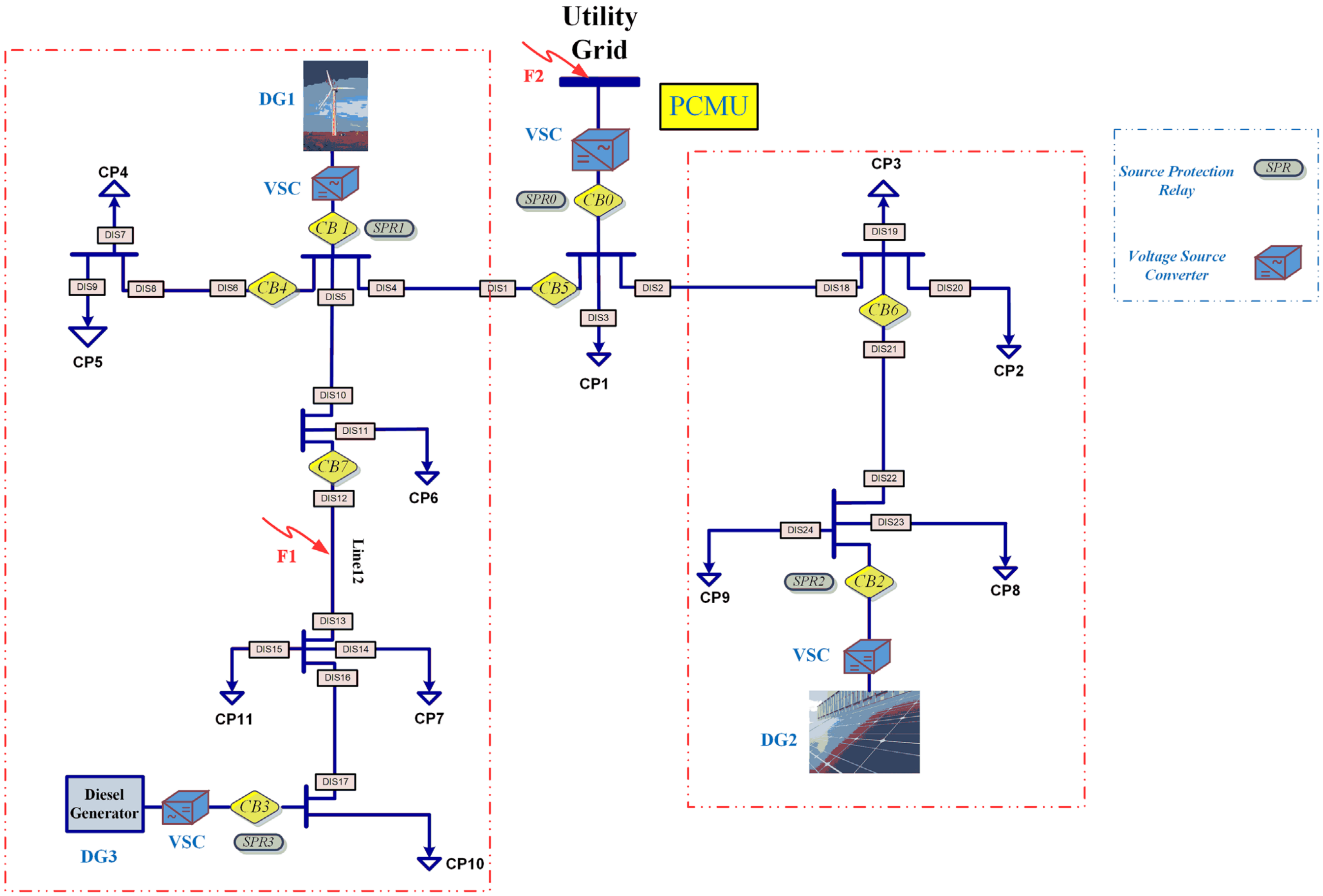

FIGURE 7 The study grid and its main components

4. Line current is measured by CT12 and CT13 and reported to PCMU.

$$CT12.Cur = '0'$$

$$CT13.Cur = '0'$$

5. PCMU opens DIS12 and DIS13 when the line current decays to zero.

$$Dis12.Opn = '1'$$

$$Dis13.Opn = '1'$$

6. CB3 and CB7 are closed. Simultaneously, the controller of DG3 changes its operating point according to the request of the PCMU. The following message determines that DG3 should work at 90% of its nominal capacity.

$$DG3.DgOuPo = '0.9'$$

7. According to the changes happened in the previous steps, that is, the faulty line isolation and DGs' new operating point, the protection units' settings are updated after executing the load-flow program. Moreover, CP10 should be turned-off to achieve the generation-load balance in the isolated part of the station's grid.

$$CP10.Opr = 'OFF'$$

$$SPR0.Set = '0.75'$$

$$SPR3.Set = '0.83'$$

8. The new status of the charging station is reported to the market participants. For example, the estimated time that each car should stay at the que is 10 min.

$$QuTim = '10'$$

5.2 | Case study 2: Fault F2 at the utility grid

In the second case study, the main supply grid, utility grid failure is considered. The following stages, determine the performance of the PCMU for this case:

TABLE 4 Transmitted Messages For the Case Study2

Application step	Device: PCMU (Computation / action)	Transferred information (Some of important messages)	Other devices (Computation/action)
Step 1	• Fault identification. • Fault Location.	• $FutDet = '1'$ • $FutLoc = '100'$	• All DGs controllers receive the fault detection notification.
Step 2	• The fault interruption and isolation messages are sent to CB0.	• $CB0.Trp = '1'$	• CB0 opens and send $CB0.\text{stat} = '0'$
Step 3	• The availability of DGs are checked. • The news operating point is sent to DGs.	• DG1.DgAvaPow = '0.9' • DG1.DgOuPo = '0.87'	• The current generated power of each DG is reported to the PCMU; e.g., DG1.DgGen = '0.8'
Step 4	• CP1 and CP3 are turned off (load shedding). • The reduction of available CPs are reported.	• CP1.Opr = 'OFF' • CP3.Opr = 'OFF' • $QuTim = '10'$ • $NoChPo = '9'$	
Step 5	• The supply grid is divided to two sub-grids by sending the appropriate commands to DISs. • DC load-flow is conducted.	• $DIS1.Opn = '1'$ • $DIS2.Opn = '1'$ • $CB5.Trp = '1'$	• DISs are opened (after opening CB5) and send the related messages to the PCMU; e.g., $DIS2.\text{stat} = '0'$.
Step 6	• New settings of protection units are calculated and set.	• $SPR1.Set = '0.9'$	• Protection units that are a part of CPMU are updated. • All protection units and SPRs are set based on the new settings to avoid protection mal-operation.
Step 7	• PCMU detects that the utility grid is restored. • Opened CBs and DISs are closed. • DGs' outputs are set according to the electricity price.	• $QuTim = '0'$ • $NoChPo = '11'$	• The smart station operates in normal condition.

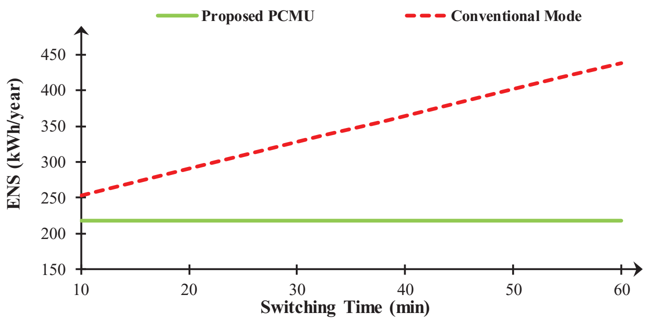

FIGURE 8 Comparison of ENS in conventional mode and proposed PCMU for different switching time values

1. Fault occurs at the upstream grid.
2. CT0 sends the measured current to the PCMU. Then, PCMU detects the fault.
3. PCMU sends the "Open" command to CB0 and this CB opens.
4. DC load flow is executed in the station's grid that has been separated from the main grid (islanded mode).
5. Since islanded DG capacity cannot fully support the charging loads, some charging points should be disconnected. Therefore, based on the load priority that has already been defined for the PCMU, the "Turn OFF" command is sent to CP1 and CP3.
6. For simple operation and protection, two islands are established. Thus, DG2 supplies CP2, CP9 and CP8, while DG1 and DG3 supply CP4, CP5, CP6, CP7, CP10 and CP11. To create these two islands, DIS1, DIS2 and DIS3 are opened.
7. DC load flow is conducted in the two new created islands and the settings of the protection units of each one are updated, if it is necessary. Thus, the new settings are sent in this stage.
8. Eventually, upstream grid is restored. This event is reported to the PCMU.
9. DC load flow is conducted again for the whole station's grid and the new settings of the protection units are determined.
10. When the utility grid restores, opened disconnectors and CBs are closed by sending the "Close" command from the PCMU. Moreover, PCMU sends the new operating points of DGs.

Table 4 shows the messages that are transmitted between the station's components for the second case study.

5.3 | Case study 3: Impact of the proposed scheme on ENS index

In the third case study, the proposed control and monitoring scheme is implemented on the test system of Figure 7, and ENS index (as one of the most-widely used reliability indices) is calculated. Moreover, the results are analysed and compared with the conventional restoration mode. In doing so, reliability data of test system and AC grid are adopted from [53, 58]. Moreover, failures of DG units and the associated interfaces are neglected [57]. Furthermore, average annual output power of DG units 1 to 3 are respectively set to 7, 5, and 25 kW, while annual average load of each charging point is assumed to be 5 kW. It should be noted that in the conventional mode, it is assumed that once a fault occurs, the closest circuit breaker(s) will isolate the faulted area. Subsequently, the loads of islanded area are shut down. Then, the closest isolators are opened by field crew so that the maximum portions of the unfaulted area can be restored. Afterwards, the powerflow is conducted in the islanded portions, DG power set points and possible load shedding are determined, and after making the necessary changes in protection settings and synchronization process by the operator, the charging points in islanded parts are restored by appropriate switching actions. The total time required to implement these steps is called switching time [52].

Based on the above discussion, the switching time in the conventional mode cannot be shorter than several minutes [52]. On the contrary, with the proposed PCMU, the whole switching process can be completed within a minute. On these bases, the values of ENS index for the proposed PCMU and the conventional restoration scheme are calculated, and the results are depicted in Figure 8. Note that since a standard value cannot be assumed for the switching time in the conventional mode, it is changed from 10 min to 1 h and the associated ENS is calculated. On the other hand, the switching time for the PCMU unit is assumed equal to 30 s. As can be observed, the value of ENS in conventional mode is proportional to the switching time, and its value increase in longer switching times. Moreover, ENS is significantly lower for the proposed PCMU, particularly at long switching times. This is because in conventional mode, the charging points of the islanded area will be shut down during the switching time, while as mentioned earlier, with the PCMU they can be restored almost immediately, given that there is sufficient power generation from local DG units. On the other hand, it should be noted that since local DG units cannot supply the whole power requirement of the charging points in the islanded areas in different fault events, the value of ENS cannot reach zero, even with the implementation of the proposed PCMU.

6 | CONCLUSIONS

The paper presents a centralized protection and control method for the smart stations. In this method, the reliability of the stations' grid is enhanced by use of an adequate and economic protection method. Moreover, the proposed PCMU is equipped with new-defined messages that are transferred between the protection and control components of the grid. By use of these messages, the overall status of the smart station is determined and therefore the station's availability can be shared by the market participants. Indeed, by use of the proposed method, not only the supply grid of the station is protected and restored after the fault occurrence, the station's availability could be shared by the costumers to reduce the required time for finding the station as well as charging and therefore facilitate the utilization of EVs. As the future work, based on this study, the impacts of the proposed PCMU and the proposed protocol on the participation and competition of the charging station in charging-station-markets can be investigated.

CONFLICT OF INTEREST

No authors have a conflict of interest to disclose.

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