Proposal of Power Control Architecture of Dynamic Wireless Power Transfer for International Standardization

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ABSTRACT: This paper reviews the proposal for a power control architecture of Dynamic Wireless Power Transfer (DWPT) for international standardization. To ensure safe and reliable power supply during vehicle operation, it is essential for ground infrastructure to accurately assess the vehicle's power demands and execute activation for power delivery before commencing DWPT. Maximizing the power received by the vehicle enhances the commercial value of dynamic charging, but excessive power transfer may damage the battery. Therefore, this study focuses on activation methods utilizing 13.56MHz short-range communication within the DWPT system and battery protection through vehicle power control using active rectifiers. These technologies have been proposed by JARI as a Japanese initiative and incorporated into the International Electrotechnical Commission (IEC) Draft Publicly Available Specification (DPAS). Establishing an interface that facilitates coordination between ground-side infrastructure with regional characteristics and vehicle-side equipment is of utmost importance.

KEY WORDS: electric vehicle, dynamic wireless power transfer, electric road system, power control, IEC, ISO, SAE

1. INTRODUCTION

Reducing CO2 emissions is an urgent issue as a countermeasure against global warming. The transportation sector aims to achieve carbon neutrality not only for CO2 emissions from vehicles during operation but also throughout the lifecycle, including material, component, and vehicle manufacturing, logistics, fuel production, and disposal/recycling [(1)(2)]. Electrified vehicles include hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV), which effectively use both engine and motor drive systems, battery electric vehicles (BEV) driven solely by motors, and fuel cell electric vehicles (FCEV) that generate electricity through chemical reactions between stored hydrogen and oxygen to drive motors. Providing a diverse range of powertrain options allows us to meet the energy strategies and infrastructure development of different regions. Therefore, a multi-pathway approach to carbon neutrality is important. There are several challenges for the widespread adoption of electrified vehicles, mainly (1) driving range, (2) battery capacity (resource acquisition, production volume, disposal, etc.), and (3) charging (waiting time, congestion at charging stations, etc.). As a solution to these issues, Dynamic Wireless Power Transfer (DWPT), which delivers power to moving vehicles, is attracting attention. DWPT includes power transfer methods utilizing electric and magnetic fields, but this paper focuses on the magnetic resonance coupling method [(3)] using coils embedded in roads and coils located under vehicle floors (Fig.1).

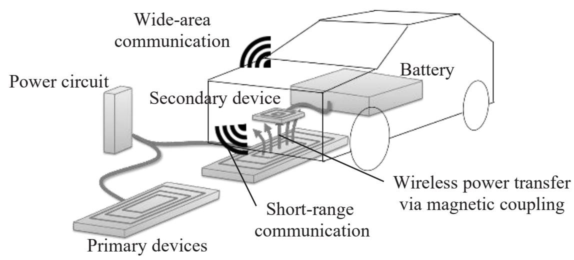

Fig. 1 DWPT System for electrified vehicle

A static wireless power transfer system (SWPT) using magnetic resonance coupling has already been commercialized as a parking lot charging system. This commercialization has been driven by the development of international standards such as SAE J2954 [4], IEC 61980 [5] -1,2,3, ISO 19363 [6], and ISO 15118-20 [7]. Activation is required to start the service, and the communication control method is specified in IEC 61980-2. When a vehicle approaches an SWPT-compatible parking lot, information is exchanged between the vehicle and the ground unit using wide-area communication like Wi-Fi® [8]. In this process, compatibility and other factors are checked for safety before moving on to the Charge session as preparation for power transfer during the WPT session. Typically, it takes several to tens of seconds from when the vehicle approaches the ground unit until power transfer begins as a Charge session. Furthermore, once the Charge session begins, the vehicle remains on the ground unit for a certain period, and the power transferred to the vehicle can be determined according to the battery's condition.

On the other hand, there are mainly two differences in DWPT, which is the subject of this paper, compared to SWPT. The first is the accommodation of high-speed travel. Use cases for DWPT range from relatively low-speed scenarios like intersections and taxi pools to high-speed applications aimed at electrifying large long-distance trucks [9], with the latter gaining particular attention in Europe and the US [10][11][12]. For example, the time to pass through a 1.5 m coil at 120 km/h is 45 ms, requiring coil pairing to be completed in a few milliseconds. The second is the fluctuation of battery power due to motor drive and regenerative braking. During DWPT, it is necessary to charge a significant amount of power to the battery, but the permissible power reception value allowed for DWPT fluctuates sharply due to the influence of motor power. Fig.2 shows an example with actual vehicle data during regenerative braking of an HEV. At around 1 second, the accelerator is released, and at around 3 seconds, regenerative braking deceleration at 2 m/s² is applied. It can be observed that the power inflow to the battery increases by about 20 kW in approximately 0.1 seconds due to regenerative braking.

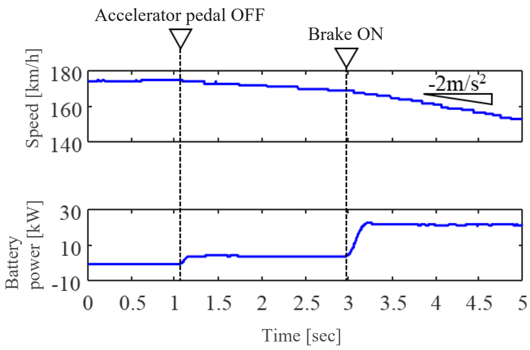

Fig.2 Regenerative brake wave form

In Section 2, a communication control method between vehicle equipment and ground equipment is proposed as a countermeasure for the first challenge, and in Section 3, a power control method is proposed for the second challenge.

2. PROPOSED DWPT COMMUNICATIN METHOD

2.1. Interoperability and General system structure

For the interoperability of wireless power transfer (WPT) ground-side equipment and vehicle-side equipment, both WPT mechanisms and communication control are necessary. The interoperability requirements for the DWPT mechanism are described in the PAS of IEC 61980-5 [13]. Based on the ideas presented in this paper, a proposal for the DWPT communication architecture was made to IEC 61980-6. In DWPT, where ground-side equipment is embedded and used in public roads, this interoperability becomes increasingly important. For the development of international standards like IEC, it is desirable to define minimum performance requirements to ensure interoperability. Diverse use cases, from urban areas to highways and from passenger cars to large commercial vehicles, might be realized through multiple system configurations, which are expected to become highly complex. For example, there are considerations such as the location and number of ground-side equipment installations, the connection methods of the equipment that manages them, and the number of vehicle-side equipment. In this proposal, a method is considered where the pairing between transferring and receiving coils is one-to-one, aiming for high scalability to accommodate all use cases. In SWPT, as described in 61980-2, vehicle-side equipment and ground-side equipment require the exchange of a large amount of information, and DWPT is also required to have a mechanism capable of exchanging a similar amount of information. Additionally, as mentioned in Section 1, the dwell time near ground equipment is very short. Taking all of this into consideration, the control communication system is proposed shown in Fig.3. The communication system structure of this DWPT consists of two types of communication methods. One is wide-area communication capable of exchanging a large amount of information, and the other is short-range communication mainly for coil pairing. While wide-area communication envisions the use of commonly used Cellular and existing road communication systems like DSRC, to achieve the low latency required by DWPT, we newly propose Point to Point Signaling (P2PS) from vehicles to ground as short-range communication. The aim was to establish a DWPT communication control system that enables support for high-speed travel by combining two types of communication methods and selectively using information necessary for the control communication system according to the session.

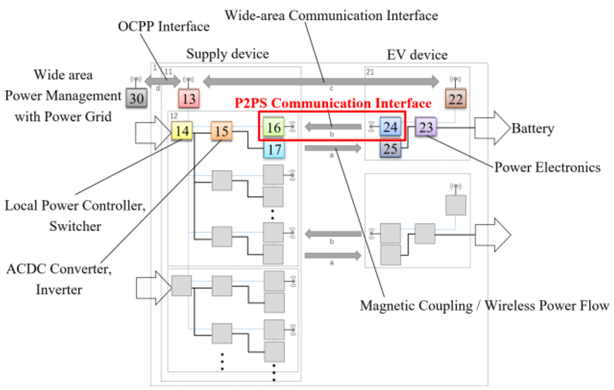

Fig. 3 An example of a general system structure

2.2. DWPT communication system concept

The proposed communication concept is shown in Fig. 4.

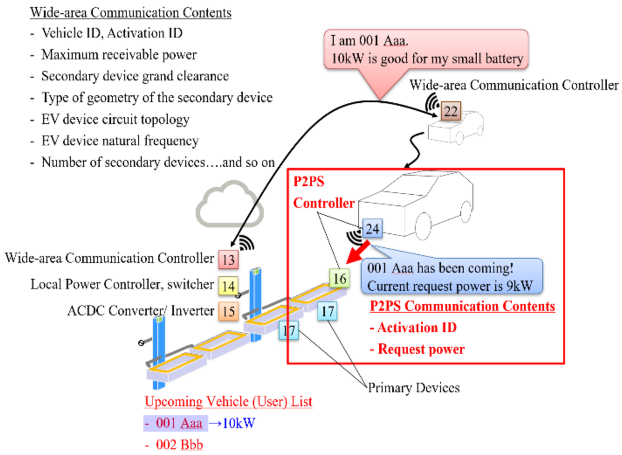

Fig. 4 DWPT communication system concept

Initially, the vehicle-side communication control equipment (EVCC), which wants to use the DWPT service, sends a request to the ground-side communication control equipment (SECC) upon starting or during travel to initiate communication. This request is made using wide-area communication, and after exchanging the necessary information for communication setup between the EVCC and SECC, the session shifts to the DWPT service session. To communicate with the SECC in the DWPT charging area that the vehicle has entered or might enter later, the use of GPS and navigation route information is effective.

Next, as the initial activity of the DWPT service session, a compatibility check between ground equipment and vehicle equipment is conducted. It verifies whether the ground equipment is compatible with the vehicle's acceptable power receiving capacity. If compatibility is confirmed in the compatibility check, an Activation ID is issued to the vehicle, completing the service authentication. Information from wide-area communication and P2PS communication is linked here using the Vehicle ID and Activation ID.

Subsequently, as the vehicle approaches the ground equipment capable of power reception and enters the range where P2PS short-range communication is possible, coil pairing is initiated. At this stage, minimal information such as the Activation ID and power reception request is shared from the EVCC to the SECC using P2PS communication, completing the final verification before power transferring. This allows for the fastest possible power change or stop instructions to the ground side according to the vehicle's condition, ensuring the ground side can understand and respond to the vehicle's status and power reception needs as much as possible right up to the power transfer. Consequently, power control within the same electrical circuit on the vehicle side and the transfer of power control instructions between the vehicle and ground equipment without wide-area communication is made possible. These communication sequences are shown in Fig. 5. There are fundamental technologies such as sensorless coil detection using the coil current on the ground side for detecting the entry of vehicle and receiving coil [14].

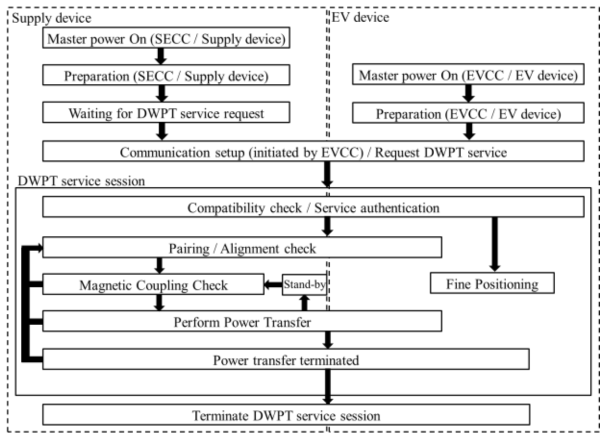

Fig. 5 DWPT communication sequence

The specific details of wide-area communication and short-range communication using P2PS are shown in Sections 2.3 and 2.4, respectively.

2.3. General communication as wide-area communication

The wide-area communication for DWPT needs to exchange various information such as compatibility and power metering, in addition to the information required for communication setup described in Section 2.2. As examples of this information, Tables 1 and 2 are proposed. These pieces of information require consideration of existing communication infrastructure in each country, as they might involve communication security measures and integration with various services. Therefore, cellular communication, Wi-Fi®, Bluetooth®, and DSRC used in systems like ETC are considered as candidates. Notably, Wi-Fi® is mentioned in IEC 15118-20 and is expected to be compatible with SWPT. However, due to constraints in communication range and setup speed, which do not satisfy the high-speed conditions required for DWPT, Wi-Fi® and Bluetooth® were excluded, and cellular communication and DSRC were selected as candidates.

Table 1 Communication information for Communication setup/ request DWPT service

Direction (Vehicle: V, Segment: S)	Information
V to S	Vehicle ID
V to S	User (billing) ID
S to V	Answer to ID registration request

Note. Communication timing: Initial / periodical refresh

Table 2 Communication information for compatibility check

Direction (Vehicle: V, Segment: S)	Information
V to S	Vehicle ID
V to S	Maximum receivable power
V to S	Secondary device grand clearance
V to S	Secondary device geometry
V to S	Secondary device DWPT class
V to S	EV device circuit topology
V to S	EV device natural frequency
V to S	Number of secondary devices
S to V	Maximum transferable power
S to V	Minimum transferable power
S to V	Maximum primary device operation frequency
S to V	Minimum primary device operation frequency
S to V	Primary device geometry
S to V	Primary device circuit topology
S to V	Supply device ID
S to V	Primary device location
V to S	Vehicle position
S to V	Activation ID

Note. Communication timing: Initial / periodical refresh

2.4. New 13.56MHz P2PS as short-range communication

A new P2PS communication method with a carrier frequency of 13.56 MHz was proposed as the communication method for DWPT. The required specifications for P2PS, such as signaling speed, are shown in Table 3, and the necessary information is presented in Table 4. The Activation ID is distributed to the vehicle during service authentication via wide-area communication, using a one-time token with minimum encryption strength. This P2PS communication enables the coexistence of millisecond-level short response times and communication security.

Table 3 Requirement/ Specification for P2PS system in unidirectional P2PS

Category	Detail
Signaling speed	More than 100kbit/s
Robustness	Communication should be established even if the antenna is buried under pavement, and with rain, snow, and snow melting agent.
Physical layer	13.56MHz carrier
Antenna type	Loop antenna, PCB printed antenna
Communication frequency	RF carrier: 13.56MHz, modulation types: OOK, ASK

Table 4 Communication information for power transfer

Direction (Vehicle: V, Segment: S)	Information
V to S	Activation ID
V to S	Power request

Note. Communication timing: Continuous

Additionally, this communication frequency has a proven track record of use in RFID. In selecting the frequency, higher frequencies were used to increase information volume to ensure communication reliability, while considering specific requirements of the DWPT system. Specifically, these include avoiding interference with WPT frequencies and adapting to the environmental requirements of roads. Both the kHz band was avoided due to the strong magnetic field of the power transfer frequency band centered around 85 kHz (79-90 kHz), and the GHz band was avoided considering the decrease in transfer coefficient between antennas due to rainwater and snowmelt on roads. As an evaluation example, the impact of road environments on 2.4 GHz is presented. Using a 32-bit microcontroller compatible with 2.4 GHz communication according to IEEE 802.15.4 and a patch-type linearly polarized antenna, the sensitivity to distance regarding obstacles was evaluated. The configuration is shown in Fig. 6, and the result example using Link Quality Indicator (LQI) is shown in Fig. 7. An average signal degradation of 16% due to water was confirmed, presumably because the radio waves (frequency 2.4 GHz) used this time were absorbed by water.

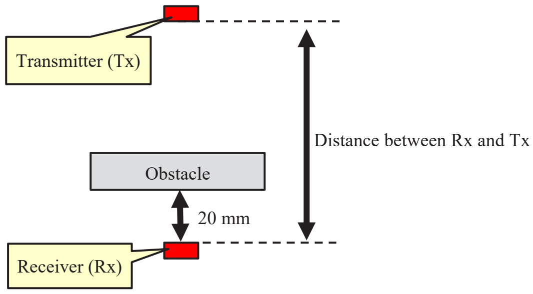

Fig. 6 Test layout of 2.4GHz RF sensors

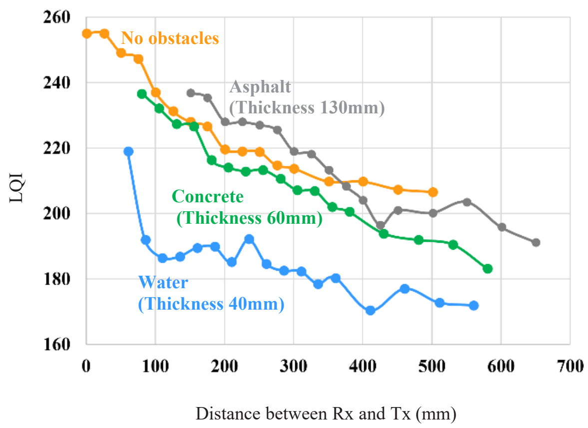

Fig. 7 Test result of 2.4GHz RF sensors

3. Proposed DWPT Power Control Technology in vehicle-side

3.1. Power Control system structure

The power control method, presented as the second challenge in Section 1, is introduced. Through short-range communication described in Section 2.4, the vehicle requests power reception requirements from the ground side, which then performs power control accordingly. Even considering communication speed and ground-side power control speed, a response speed of several tens of milliseconds is expected. On the other hand, as shown in Fig. 2, since the motor power change is 2kW/10ms, it can be managed by keeping a margin for the battery's charging capacity.

However, considering a future world where DWPT becomes widespread, it is easy to predict that batteries will become smaller than those in current BEVs. Therefore, it was considered necessary to have a mechanism for power control on the vehicle side to achieve high response power control. This stems from the philosophy of vehicle manufacturing that aims to complete battery protection, i.e., safety, within the vehicle.

Consequently, research on methods for power control on the vehicle side was conducted, and studies by Tsuge [15], Ikemura [16], Nagai [17][18][19], and Fujita [20] demonstrated their effectiveness. The electrical circuit of the vehicle-side power control method is shown in Fig. 8, and the control mode using active rectifiers is shown in Fig. 9.

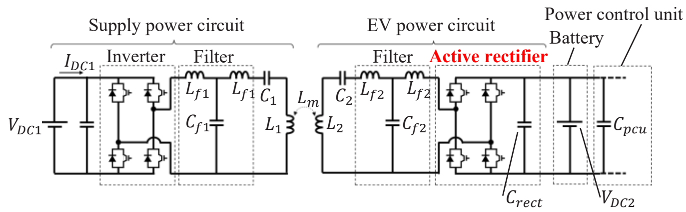

Fig.8 Double-sided LCC circuit for DWPT

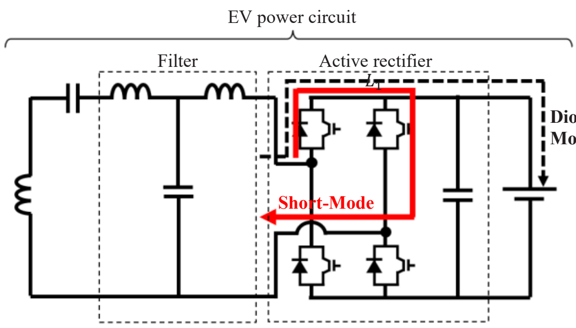

Fig.9 Diode-mode and short-mode in active rectifier

3.2. An example of Power Control Experiment

To apply vehicle-side power control, including active rectification, an overview of experiments conducted by modifying a commercial PHEV is shown in Fig. 10. The block diagram of feedback control using battery DC current values is shown in Fig. 11, a photograph of the vehicle during power control is shown in Fig. 12, and the results are shown in Fig. 13. It demonstrates that with power control, the received power is equivalent to the power value set as the target, compared to without power control.

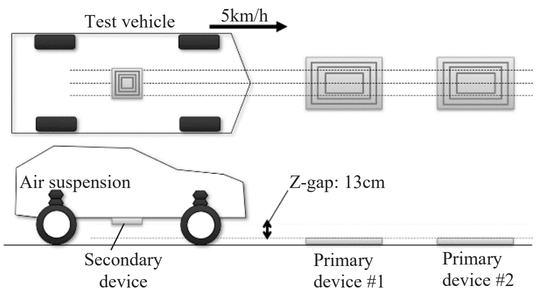

Fig.10 Arrangement of test vehicle and coils

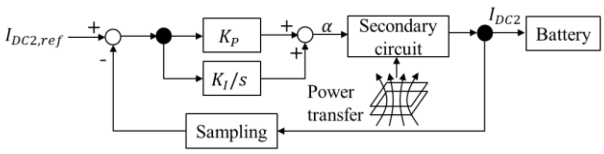

Fig.11 Block diagram of feed-back control

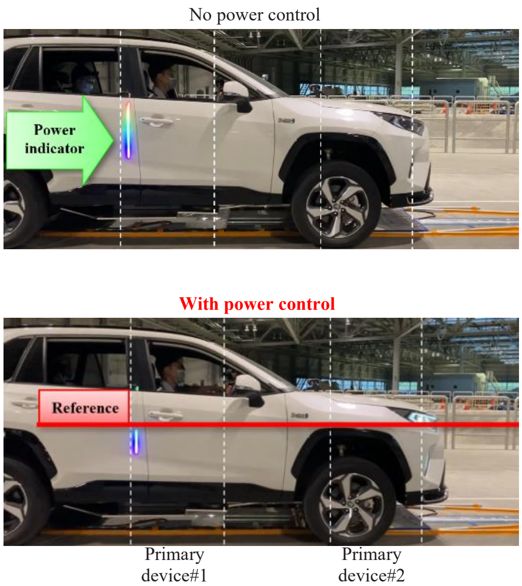

Fig. 12 Receiving power in dynamic test with/without control

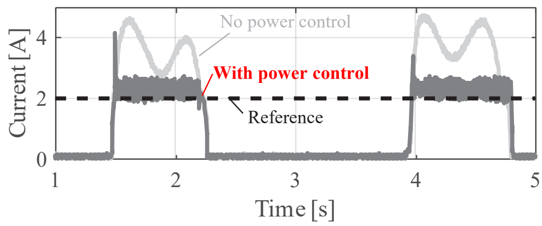

Fig.13 DC current at battery in dynamic test with/without control

Furthermore, such power control during DWPT execution was considered in the IEC 61980-6 DPAS. The feedback control loop is shown in Fig. 14, and an example of a controlled power transfer trajectory is shown in Fig. 15. It is anticipated that the amount of power transferred to the battery may change even during power transfer. One point to note here is that power control exists on both the ground side and the vehicle side (Fig. 13). To avoid interference between the two feedback controls, various methods can be considered, such as setting standards for each control and communication speed. However, it is necessary to clarify the relevant requirements for their selection.

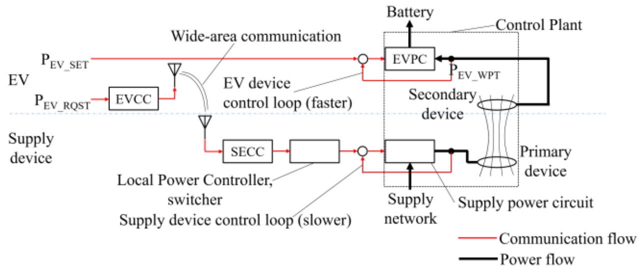

Fig.14 Block diagram of communication system

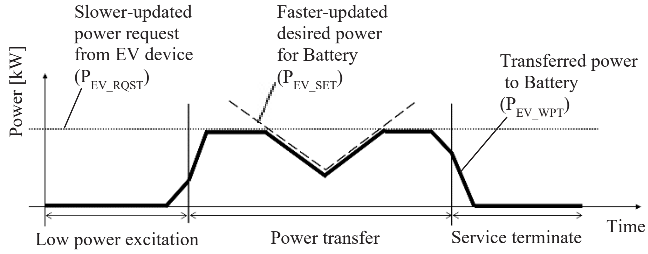

Fig.15 An example of controlled power transfer trajectory

4. International Standardization for Coordination between Vehicle and Infrastructure

While ground-side and vehicle-side equipment are different as hardware, they are strongly interconnected due to the nature of forming a single magnetic or electrical circuit system. It is expected that the providers of ground-side equipment and vehicle-side equipment will be different. Therefore, international standardization to establish a cooperative interface between these is extremely important.

5. Conclusion

A power control architecture was examined considering the use cases of DWPT and proposed for international standardization. In communication control, by utilizing wide-area communication and P2PS short-range communication, low-latency communication was ensured between vehicle equipment and ground equipment to secure power reception opportunities. Furthermore, in power control, a highly responsive power control and power request method were considered according to power balance fluctuations in DWPT vehicles. These were discussed among JARI members and proposed as a Japanese proposal to IEC 61980-6, leading to the issuance of DPAS for the PAS of communication control. Please note that these figures and tables represent the content at the time of the Japanese proposal, and the official figures and tables should be referred to in the latest IEC standards.

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