Study and Field Test of Power Line Communication for an Electric-Vehicle Charging System

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Abstract—**A battery-charged electric-vehicle (EV) technology has recently been developing fast due to energy efficiency and environmental problems. To commercialize these EVs, the EV charging infrastructure should be completely installed. Power line communication (PLC) is a technology designed to use the existing power lines and support communications. As such, its application is under study in diverse fields such as in the outdoor, in-home, in-plane, in-ship, and in-vehicle scenarios. An ISO/IEC 15118 standard is pushing to standardize PLC as a technology that supports EV charging systems. To apply PLC to the EV charging system, this paper investigates the EV and EV charging structures and analyzes requirements for applying PLC. The PLC modem performance was also tested with the charged EV.**

Keywords: Power line communication, electric vehicle, electric-vehicle charging system, vehicle-to-grid

I. INTRODUCTION

With a rapidly growing international concern about limitation and environment of carbon emissions, a smart-grid technology designed to optimize energy efficiency has been fast developing. The smart grid is a kind of power network designed to apply ICT (information and communications technology) to the existing power network to enable real-time interactive exchange of power use between power supplier and consumers, thereby distributing energy demands and maximizing power efficiency. As such, it is a next-generation intelligent power network. To enable its practical use, it is essential to develop key technologies such as interactive ICT as well as smart metering, distribution-type energy management, power quality compensation, electric-energy storage, energy monitoring and diagnosis and security technologies. Among these applications, an electric-energy storage technology will further create effect of distributing energy demands if the energy storage battery and electric-vehicle (EV) technology are widely applied [1]. To enable such EV's to successfully settle in global automobile markets, an EV charging infrastructure should be perfectly installed. Moreover, to support stable charging and diverse value-added services, the issue on the communication facilities between EV's and charging systems should be addressed. An international standards organization ISO/IEC has selected PLC (power line communications) technology as a communication technology for the EV charging system, and is pushing to standardize the IEC 15118 vehicle interface into a grid communication interface [2].

For the last several years, PLC has been extensively studied in the outdoor, in-home, in-plane, in-ship, in-vehicle, and other scenarios due to its low installation cost and easy configuration, among its other strengths. To apply PLC to diverse fields, its channel characteristics, such as its frequency response and noise in diverse fields, and its impedance and system application methods, should be studied. In [3], narrowband and broadband PLC theories and applications were investigated, and PLC channels in homes were simply modeled [4]. In [5], PLC channels were tested and analyzed in ships, and in [6], HomePlug-1.0-compatible PLC modems were tested in a cruise ship. In [7], in-vehicle power line channels were modeled and analyzed, and in-vehicle high-speed communication methods were studied [8]. With the EV emerging as an important issue, the research on EVs where mechanical and electronic technologies are merged in a complicated manner is fast progressing. In [9,10], the results of their analysis of the EV issues and of some field tests are presented.

In this paper, to define the complete EV charging process, and to guarantee high-speed communication for status information and stability as well as diverse user services, a PLC modem was configured to interface with an EV and its charging system; and with the EV charged, the performances of HomePlug AV, ISO 12139-1 [11], and G3-PLC were tested. Section II describes the EV and its charging system. Section III presents the results of analysis of requirements for applying PLC to the EV charging system. Section IV presents the results of testing of PLC modems with a charged EV, and briefly discusses the PLC modem for the EV charging system. Finally, the conclusions are drawn in section V.

II. OVERVIEW OF THE EV CHARGING SYSTEM

A. EV Charging System

The EV charging system is classified into the AC charging station, which is based on the slow-charging method that uses below 1,000V standard AC supply voltages (as per IEC 60038), and the DC charging station, based on a fast-charging method that uses below 1,500 V DC voltages. The ISO/IEC is pushing to standardize the IEC 61851 EV conductive charging system [12]. Moreover, what is important for EV charging is a mode of vehicle couplers and vehicle inlets that connect an EV and the EV charging system, and the IEC 62196 plugs, socket outlets, vehicle connectors and vehicle inlets. The conductive charging of EV's is being standardized [13].The AC charging station is a system that receives electricity from the AC power and supplies it to the EV, and then converts the AC power received by the EV into DC power via the on-board charger

(OBC) and charges it in the battery. The DC charging station receives electricity from AC power, converts it into DC power, and charges it in the battery. Both stations need the input/output (I/O) system for user charging information, a control system, a smarter meter, and the communication system that connects the operating system for the charging system and the billing with the communication system for controlling the EV charging. Fig. 1 shows the EV charging system.

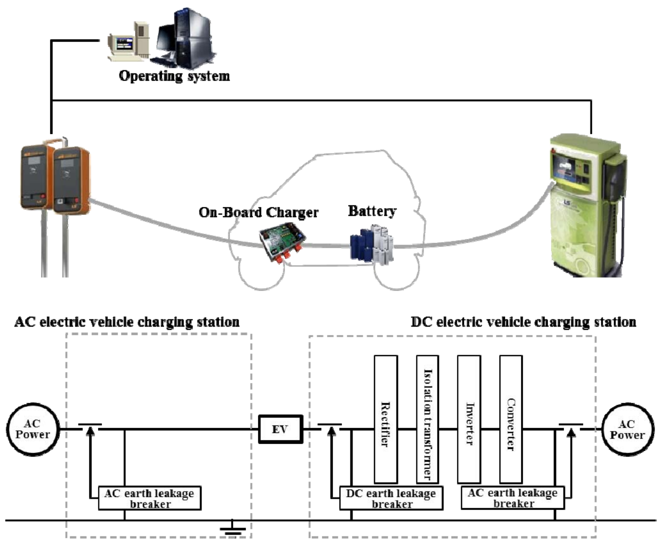


Fig. 1. EV charging system.

The vehicle connector/inlet modes somewhat vary by country, centering on the U.S., Europe, and China, and IEC 62196 defines various charging modes and plug types. Fig. 2 shows the representative vehicle interface configuration type for the AC and DC charging stations. Vehicle interfaces 1 and 2 of the AC charging station are utilized as the AC power terminal, and vehicle interface 3 of the AC charging station is utilized as the ground terminal. The control pilot detects the voltage level of the PWM signals so as to judge the charging status, and the Connect switch detects the vehicle connector linkage status. The vehicle interface of the DC charging station supports the battery management system (BMS) wake-up (12 V) designed to supply power to BMS, and the controller area network (CAN) designed for delivering charging information.

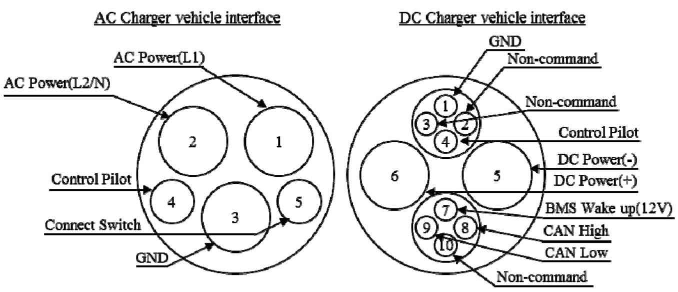


Fig. 2. Vehicle interface.

B. Charging technology in EVs

An EV, where mechanical and electronic technologies are merged in a complicated manner, needs the following technologies to be charged. Fig. 3 shows the key EV technologies.

- EV-ECU (electric-vehicle electronic-control unit): Controls the AC/DC charge, motor/torque, energy management, etc.
- Connector: A system connected to the EV charging system (EV generally provides two vehicle connectors to support both the AC and DC charging stations.)
- OBC (on-board charger): Converts the AC supplied by the AC charging station into DC and charges it in the battery
- LDC (low-voltage DC/DC converter): Converts a high battery voltage into a low battery voltage (12 V); charges a 12V auxiliary battery and supplies power to electric/electronic subassemblies
- Inverter: Converts the battery's DC voltage into AC voltage, and supplies power to the driving motor
- BMS (battery management system): Measures the cell voltage, cell outside temperature, cell internal resistance, and charge/discharge current; protection against overdischarge/overcharge and overcurrent; used for cell balancing and CAN communication
- Battery: A system for storing high-voltage electric energy

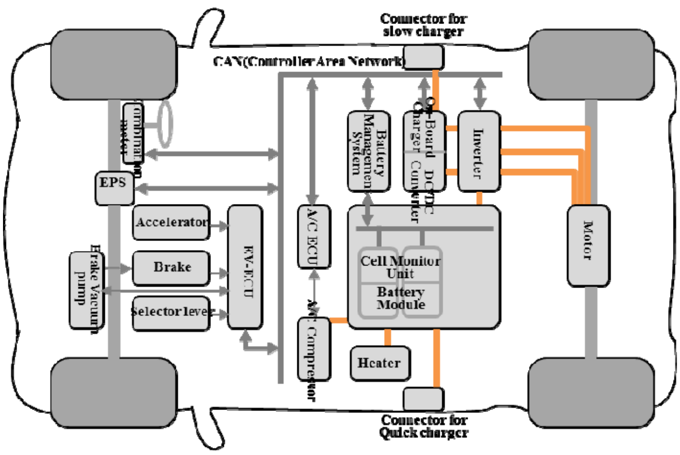


Fig. 3. Key technologies of EV system.

As briefly explained, to charge an EV with the AC charging station, the EV and AC charging station should be connected via the exclusive connector. Thereafter, the charging status of the EV and AC charging station are judged via the connect switch circuit, control pilot circuit, and PWM signal. If all the processes are normal, the AC charging station will supply AC power to the EV, and the EV will convert the supplied AC power into DC power via the OBC to store it in the battery. When charging an EV at the AC charging station, the battery status information (cell voltage, cell outside temperature, cell internal resistance, charge/discharge current, etc.) and the charging status information (remaining battery charging amount, charging error, etc.) for safety cannot be provided. In the case of the DC charging station, the battery and charging status information can be provided via CAN, but diverse services for vehicles to grids and users cannot be provided.

III. PLC REQUIREMENTS FOR THE EV CHARGING SYSTEM

When charging an EV, to guarantee all the charging processes/status information, safety status, and diverse user services, the PLC should be configured considering the communication stack for the EV charging system, the coupling interface of the PLC signal, and the power supply of the PLC modem.

A. Communication Stack for the EV Charging System

In Fig. 4, for the EV charging system, the communication stack (Smart Energy Profile 2.0) and the ISO/IEC OSI reference model are compared. In ISO/IEC 15118-3 (physical-layer and datalink layer requirements), the PLC can be considered the media access control (MAC) sublayer of the datalink and physical layers. In ISO/IEC 15118-2 (technical protocol description and open systems interconnections layer requirements), IPv6-based SEP 2.0 is considered an OSI layer 3-7. The I/O control path interfaces higher layers to hardware I/O control (e.g., EV-ECU, BMS, and OBC), and the hardware in an EV, as shown in Fig. 3, is connected to the CAN. To provide I/O SAP (service access point), as in Table 1, the PLC modem for the EV charging system must provide a CAN interface. Association control provides full functionality for the EV-to-EV charging system association and initialization. The control SAP provides methods for indicating the PLC line status, the association, and the error messages to the higher layers. Communications media are the cable assemblies that connect the EV and the EV charging system. It is a physical medium for carrying PLC signals. The signal-coupling interface, which describes the method of coupling the PLC signal on the communication media, is described in part B.

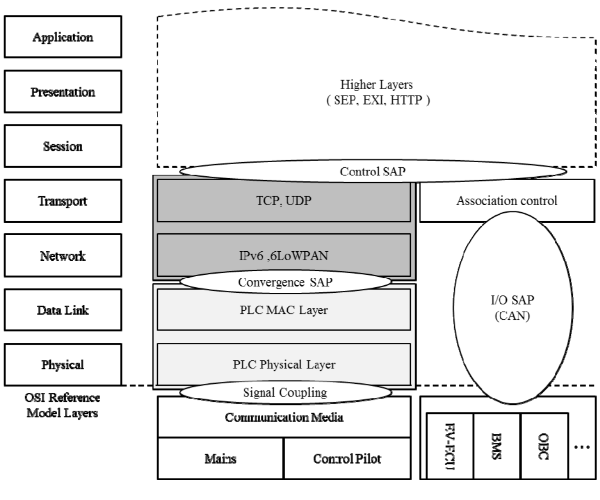


Fig. 4. Communication stack (SEP 2.0) for EV charging system.

TABLE I. CHARGING AND BATTERY INFORMATION

Message	Entity to Support
Charging status information	
- Charging mode	- BMS
- Start of charge, end of charge	- PLC, EV-ECU, EVCS
- Reservation charge	- EVCS
- Charging error	- EV-ECU, EVCS
- Charging control	- PLC, OBC
- Charge current, voltage, power	- OBC, BMS
Battery status information	
- Battery SoC (%)	- BMS
- Battery status	- BMS
- Battery temperature	- BMC
- Constant current/voltage charge	- EVCS
Authentication	
- EV ID or customer ID	- PLC, EV-ECU
- EV charging system ID	- PLC, EVCS
- Authentication information	- EV-ECU, EVCS
*Other **services***	
- Price/time/load information	- EVCS
- Meter data	- Smart meter
- Billing	- Billing device
- Security	- EVCS
- Other EV information	- Smart device

B. Coupling interface of the PLC signal

Fig. 5 shows that the EV and the AC charging system are connected via the AC charger cable assembly (SAE J1172). As explained, the AC charger interface has five units, and to use the AC charger cable as the PLC signal transmission line, the PLC signal distortion and reflection loss should be minimized through impedance matching. Moreover, the main line (power line) and the control pilot line features should be considered. The main line of the AC charger cable flows at 220-240 V and a maximum 32A current, and is connected to the EV electronic devices (e.g., BMS, OBC, inverter, and DC/DC converter). This creates noise in the frequency band. When using the main line and the coupling power line signals, the PLC signal transmission line should be coupled behind the power switch; and to couple it in front of the power switch, the front and rear of the power switch should be connected via the bypass filter. When using the control pilot line and the coupling power line signals, the PWM 12V square wave should be prevented from being damaged and distorted by considering the inductive coupling method.

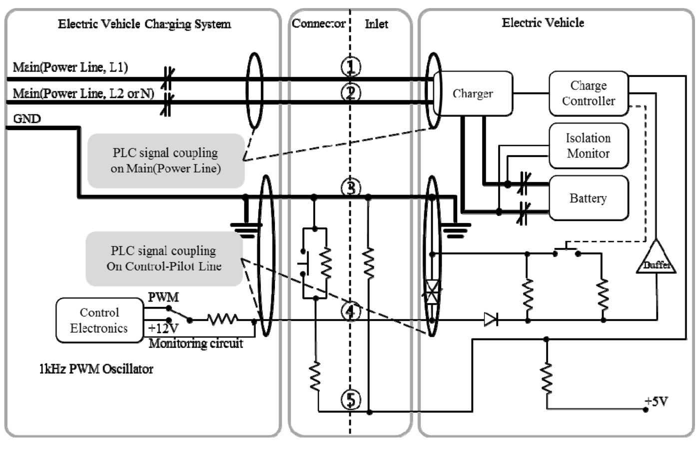


Fig. 5. AC charging system configuration (IEC 61851-22).

C. *Power supply of the PLC modem*

Fig. 6 shows a sketchy diagram of the state of the EV charging system. The PLC modem, from the time the vehicle connector is connected to the EV, undertakes EV-EV charging system communication and can control all the charging processes. Thus, the PLC modem for the EV charging system, unlike the existing PLC modem, should separate the power supply line for the PLC modem from the PLC signal transmission line, as shown in Fig. 7. This is because the PLC modem should operate and control all the charging processes before power is supplied to the EV via the main line of the AC charger cable assembly.

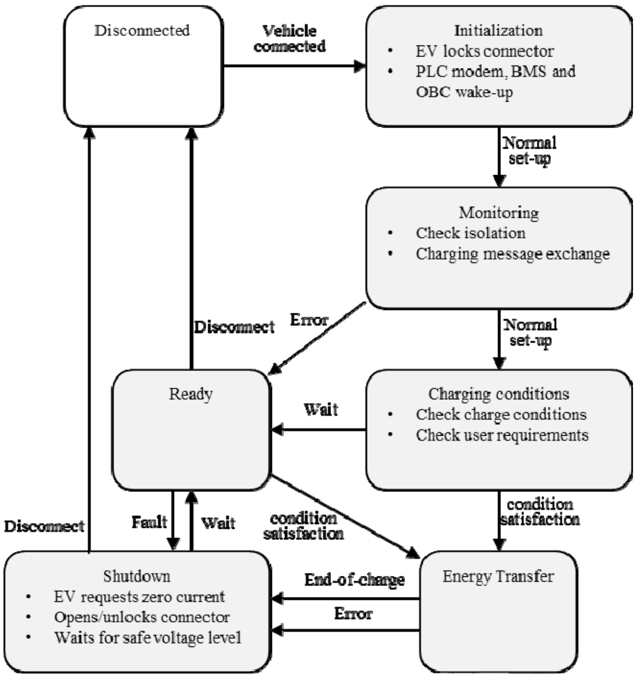


Fig. 6. State diagram of EV charging system.

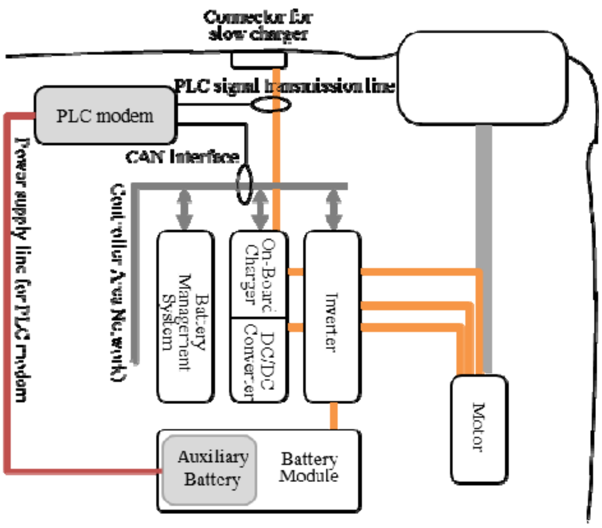


Fig. 7. PLC modem for EV charging system.

IV. PLC Performance in the EV Charging System

The EV charging system configuration encompasses one AC charging station and one EV, and the PLC modem was tested using the narrowband PLC (G3-PLC) and the broadband PLC (HomePlug AV, ISO 12139-1). For the PLC signal transmission line, the AC charger cable assembly (SAE J1172) main line was applied. Table II shows the technical features of the EV, AC charging station, and AC charger cable assembly that were used in the field tests.

TABLE II. EV Charging System Configuration

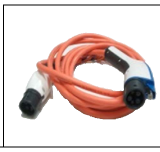
Image	Technical Specifications
EV (7kW single motor)	
	- Min. turning radius (m): 3.8 - Max. speed (km/h): 60 - Motor: 7kW single motor - Battery: Li-polymer 72V-135Ah - Charger: 110/220V(50-70Hz) - Controller: 72V
AC charging station (7.7 kW)	
	- Max. output power/nom. voltage: 7.7 kW - AC input: Single-phase 220 V - AC output: 220 V, 32 A (SAE J1172) - Power usage: Smart meter - Communication pilot, TCP/IP, CAN, RE232
AC charger cable assembly (SAE J1172)	
	- Single-phase electrical systems with up to 240 V and 70 A - The round 43-mm-diameter connector has five pins and will support communication over power lines to identify the vehicle and to control the charging.

Fig. 8 shows an observation of noise created in the main line during the EV charging. In the main line, it was confirmed that the noise level in the narrowband (10-450 kHz) ranged from -30 to -85 dBm, whereas in the broadband (1-30 MHz), it ranged from -65 to -75 dBm. As the heavy load is connected to the EV and the AC charging station, according to the instantaneous load motions, a somewhat irregular impulse noise is created. The noise, which is created in the low-frequency band below 150 kHz, is the EV OBC switched-mode power supply (SMPS) noise and the noise created in the BMS load. The noise, which is consistently created in the high-frequency band, is the EV load and the noise created in the OBC, and its features vary according to the OBC manufacturer.

Fig. 9 shows an observation of PLC signals during the EV charging. It shows how the main line noise affects the PLC signals. In the case of ISO 12139-1 and HomePlug AV, the PLC modem's transmitter output level is higher than the noise in the communication channel, thereby not greatly impacting the transmission signals. CENELEC-A (32-95kHz) and CENELEC-B (98-121kHz), which utilize the below-150kHz frequency band of G3-PLC, offer high noise levels, making it difficult to guarantee excellent PLC performance. This is because in IEC 61851-22, the conductive-emission limit was limited to the 150 kHz-30 MHz frequency band. In other levels (150 kHz-30 MHz), the PLC modem's transmitter output level is high, supporting smooth communication.

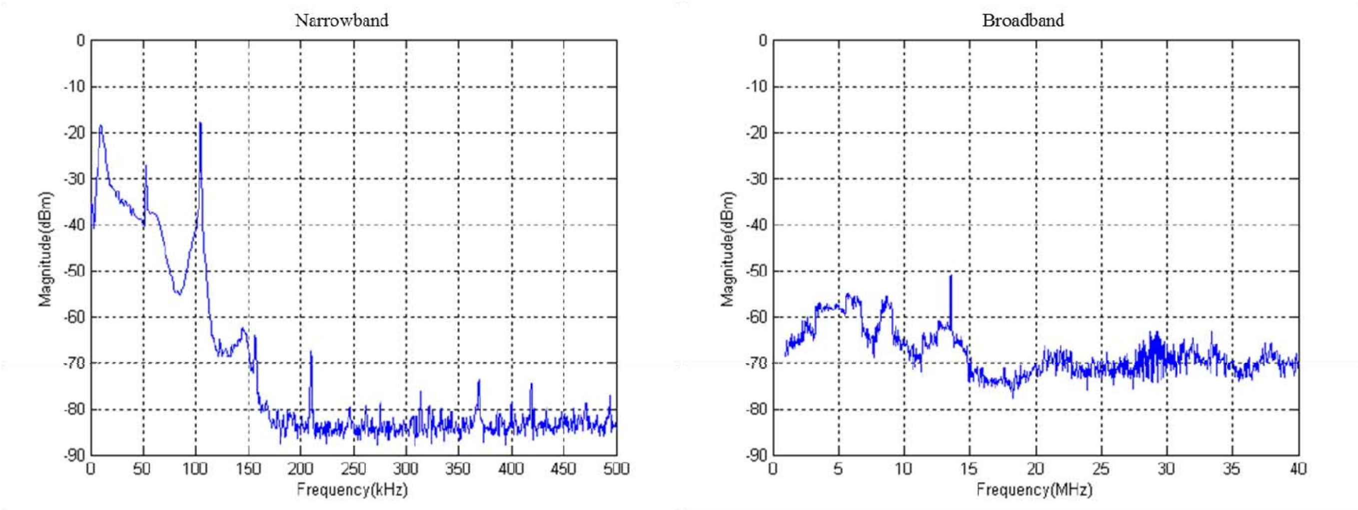


Fig. 8. Noise spectrum of main line (power line).

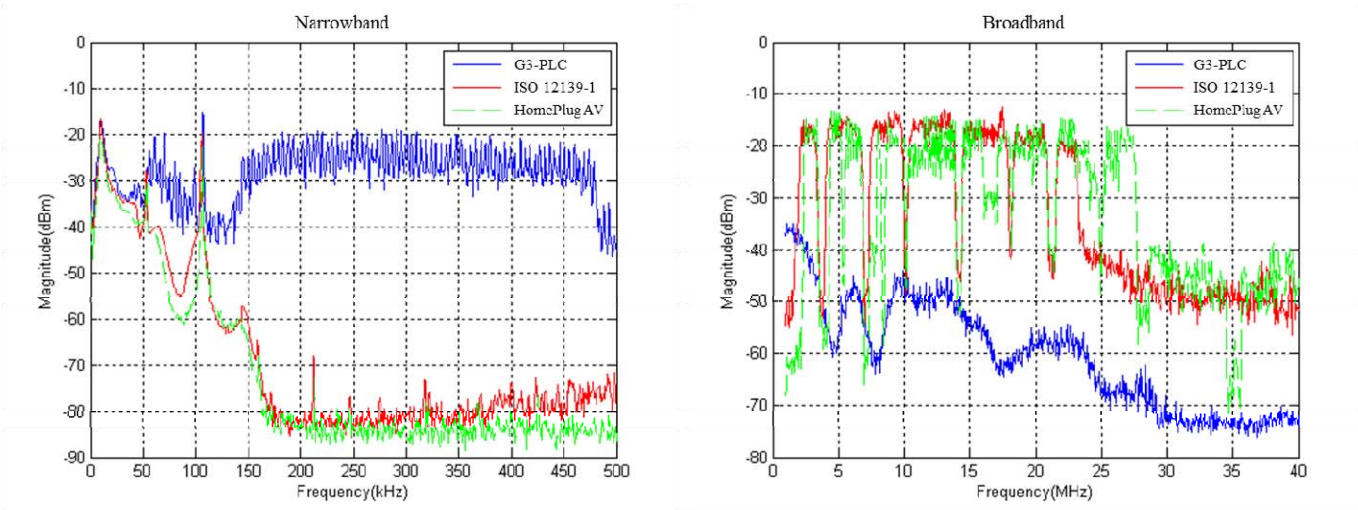


Fig. 9. PLC signal and noise spectrum of main line (power line).

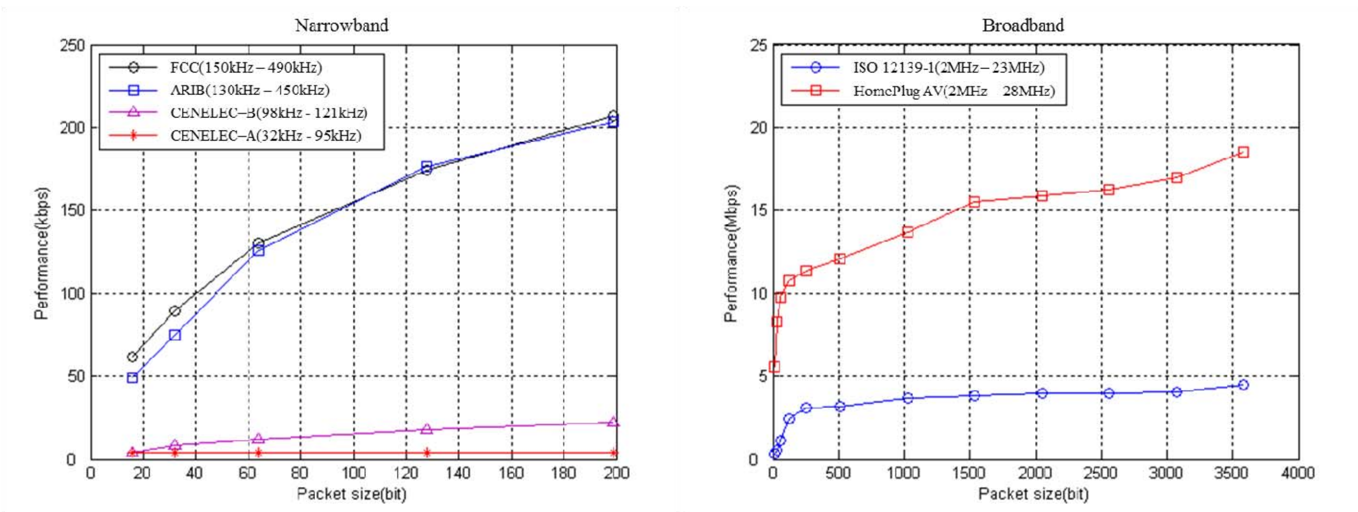


Fig. 10. PLC modem performance.

Fig. 10 shows the G3-PLC, ISO 12139-1, and HomePlug AV performances. The narrowband PLC modem G3-PLC's CENELEC-A mode may perform much more poorly than the other modes. As explained, this is because below 100 kHz, the noise is greater than the PLC signals. The CENELEC-A mode is a frequency band that goes beyond the IEC 61851-22 conductive-emission limit, thus not guaranteeing excellent PLC performance. The FCC and ARIB modes support the above-130kHz frequency band and use a broader frequency band, thus showing a somewhat high level of PLC performance. The broadband PLC modem ISO 12139-1 supports the 2-23MHz frequency band, whereas HomePlug AV supports the 2-28MHz frequency band. As HomePlug AV uses a frequency band broader than that used by ISO 12139-1, it shows a high performance level. Through this test, the main-line-noise features were analyzed, and the impact of the noise on the PLC signals was confirmed.

V. Conclusion

In this paper, to apply the PLC modem to the EV charging system, the overall structure and technologies of the EV and the EV charging system were studied, and methods designed to apply the PLC modem to the EV charging system were analyzed. Moreover, through the PLC modem (G3-PLC, ISO 12139-1, and HomePlug AV) field tests, it was found that when the main line of the AC charger cable assembly was utilized as the PLC transmission line, it was difficult to guarantee the excellent performance of the G3-PLC CENELEC-A mode, which utilizes a narrowband below the 150kHz frequency. The results of this paper can find their applications in EV charging system based on PLC infrastructure.

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