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Overview of Talkative Power Conversion Technologies

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ABSTRACT Power Line Communication (PLC) and Simultaneous Wireless Information and Power Transfer (SWIPT) are popular examples of applications, where power and information are transmitted simultaneously. In most cases, different devices have been used to generate the power and communication signals independently. Usually, the information is superimposed onto the power signal using an external modulator. Recently, power converters have been used to generate pulses not just for power conversion but also for information transfer simultaneously. This approach represents a fundamental difference because it exploits the signal processing potential of Pulse Width Modulation (PWM), where for power conversion only the average pulse width is used, while the information is represented by the harmonics instead of being filtered out, as typically done in power electronics. The concept of embedding information into the switching ripple generated by a switched-mode power converter has recently been dubbed Talkative Power (TP), in this paper referred as Talkative Power Conversion (TPC). TPC technologies are reviewed in non-isolated and isolated converters in this paper. Potential applications include visible light communications, battery management systems, switching reluctance generators/motors, microgrids, and wireless electric vehicle charging stations. Finally, trending topics are identified.

INDEX TERMS Talkative power conversion, pulse width modulation converters, power line communication, switching ripple communication, simultaneous wireless information and power transfer.

I. INTRODUCTION

Since renewable resources are geographically dispersed with intermittent and random characteristics, distributed power generation systems are established to effectively harvest and utilize renewable energy. Distributed generations improve the network performances, e.g., reduce line losses, improve voltage profile, attenuate the overload, and as a consequence increase penetration of renewables [1]. In modern electricity grids, the penetration of power converter-interfaced resources, e.g., battery banks, electric vehicle charging stations, wind turbines, photovoltaic panels and electric motors, is continuously increased [2]. To control and manage these power converter-interfaced resources, Communication (COM) infrastructure is also required.

Conventional PLC systems embed the information in signals superimposed onto the same channel as used for power transfer, thus avoiding using an independent communication system [3], [4]. Nevertheless, conventional PLC systems require passive inductive or capacitive coupling and a modem. Moreover, using PLC along with a Power Electronic (PE) converter might lead to interference [5], [6]. Sequential PLC is proposed in [7] to overcome the aforementioned problem by transmitting the data in the interval of power OFF. In the COM community, this technique is called time sharing and requires some hardware efforts but less than for conventional PLC. Time sharing PLC is suitable for short distances.

Power converters can directly transmit data to the connected grid without any additional hardware or hardware modifications. Data can be embedded into the pulses by modifying the switching characteristics. In [8], this technology was dubbed Talkative Power (TP). Considering that the modulation of power and data happens in the power converter without additional hardware, i.e. power conversion stage, it is referred as Talkative Power Conversion (TPC) in this paper. TPC has been called zero-additional-hardware PLC in [9]. Other researchers have called it from the signal perspective such as Power & Signal Multiplex Transmission (P&SMT) [10], Power and Signal Synchronous Transmission (PSST) [3], and Power/Signal Dual Modulation (PSDM) [11], [12]. Nonetheless, none of these definitions is wide and precise enough to be taken into account for PLC and Simultaneous Wireless Information and Power Transfer (SWIPT) while fulfilling the concept of power conversion, transmission, and distribution. Moreover, the term signal does not comply its original definition as a signal may not necessarily carry information [13]. In practice, power and data both appear in form of current and/or voltage signals.

Considering the modulation process in a power converter, TPC can be implemented in several ways: superimposing the data on the reference modulator, i.e. reference modification, and carrier modification. Superimposing the data on the reference is a straightforward method to realize TPC. This method is called Reference-Signal-based TPC (RS-TPC). Traditional digital modulation strategies including Amplitude Shift Keying (ASK), Frequency-Shift Keying (FSK), Phase-Shift Keying (PSK), Pulse Position Modulation (PPM), and Orthogonal Frequency Division Multiplexing (OFDM) can be flexibly implemented [14], [15]. The second way of realizing TPC is to change the carrier in the modulation process. This method is called Carrier-Signal-based TPC (CS-TPC). A hybrid combination of RS-TPC and CS-TPC has recently been proposed in [12]. Alternately, TPC modulations can be implemented fully digitally [16].

PWM techniques suitable for TPC include PWM-FSK, PWM-PSK, PWM-PPM, and PWM-Frequency Hopping-Differential PSK (PWM-FH-DPSK) [17], [18]. Besides, PWM Spread Spectrum (PWM-SS) communication was also proposed to increase the resistance against interference [19]. As multiple electric-devices are communicated, multiple access technologies such as Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), and Code Division Multiple Access (CDMA) were employed, respectively [20]. TPC modulation methods have been applied in both non-isolated converters and isolated converters (with a medium/high frequency transformer). In [21], TPC modulation was employed for multiple buck and boost converters and it was also investigated for a full-bridge converter via phase shift modulation [22], [23].

There are many applications of TPC modulation in both wired and wireless systems. Concerning wired communication, it has been applied to Battery Management Systems (BMS) and switching reluctance generators/motors [24], [25], [26], allowing the signal transmission for condition monitoring, fault diagnosis, and efficiency optimization easily achieved. Regarding wireless communication, TPC has been employed in visible light communication and wireless electric vehicle charging stations, far extending connections of electric devices and reducing the establishment of both signal and power lines [27], [28]. Recently, an overview of TP application in microgrids (μ-grids) has been presented in [11] where TP is referred as PSDM. Different modulation and converter topologies have been compared in terms of data rate, distance, and Bit Error Rate (BER). Despite the detailed technical discussions, the paper does not provide a comprehensive vision of the TP concept as well as its potential applications in other disciplines.

The motivation behind this work is to overview the state-of-the-art of the TP concept and its potential applications in electrical power grids and other disciplines. TPC modulations are reviewed and classified as well as its applications in BMS, wireless EV charging, and drive systems extending the previous work in [29]. Prospective applications of TPC in wireless and wired applications are addressed. In particular, wireless power transfer employing TPC might enable microwave energy harvesting and medical implants. Possible applications for optical fibers are outlined. It has been shown that new converter topologies can be realized using the TPC concept which can be explored as a possible future research direction.

This review paper is structured as follows. TPC principles are explained in Section II starting from fundamental requirements for PE and COM. Section III describes TPC modulations and classifications. Wired and wireless TPC techniques adopted in DC/DC converters are studied in Section IV. Then, practical applications of TPC in both wired and wireless systems are detailed in Section V. Future perspectives and developments of TPC in other disciplines are described in Section VI. Finally, this paper is concluded in Section VII.

II. TPC BASICS

This section provides the basic definitions and concepts which are required to fully understand TPC. TPC explanations are evolved from COM and PE modulation in the following subsections.

A. COM MODULATION

In a so-called baseband COM system, the information is represented by a train of weighted baseband pulses. If the baseband signal is transformed to another frequency, then a carrier-based COM system is obtained. The choice of the baseband pulse is a trade-off between transmission bandwidth, intersymbol interference, detector complexity, and probability of error.

Given a sequence $a_0, a_1, a_2, \ldots$ of data symbols and a baseband pulse $p(t)$, the transmit signal can be written as

$$s(t) = \sqrt{E_s} \sum_n a_n\, p(t - nT_s), \tag{1}$$

where E_s is the energy per symbol and T_s is the symbol duration. The narrowest signal bandwidth without causing

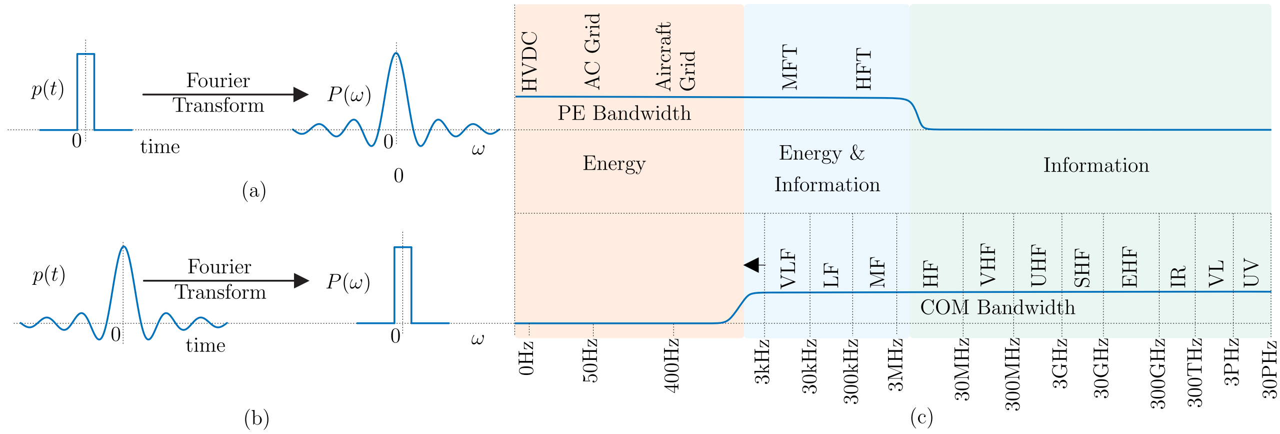

FIGURE 1. Time and frequency domain properties of pulses: (a) square pulse, (b) Nyquist pulse, (c) the frequency bands where most of PE and COM applications are designed.

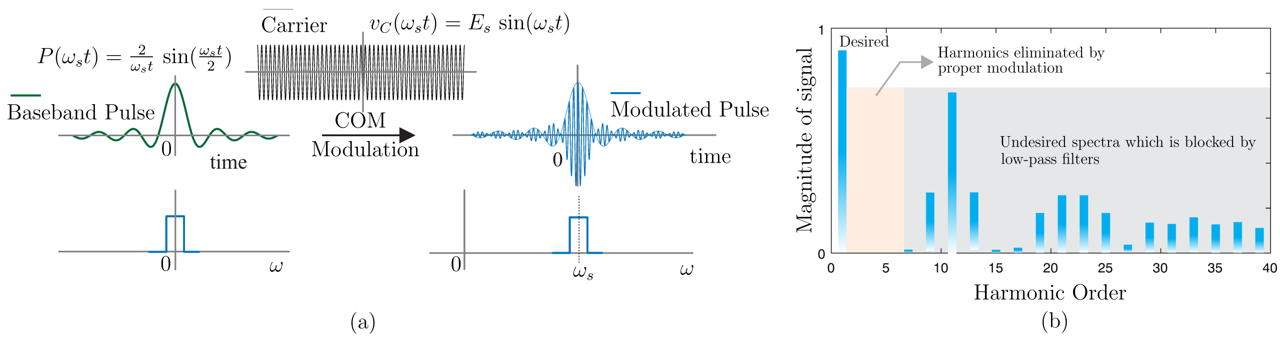

FIGURE 2. COM and PE fundamental modulations: (a) simple modulation of a Nyquist baseband pulse, and (b) carrier-based double-edge naturally sampled SPWM and its harmonic spectra for $f_{sw} = 11f_0$.

intersymbol interference is obtained by a Nyquist pulse:

$$p(t) = \mathrm{sinc}(t/T_s) = \frac{T_s}{\pi t}\sin(\pi t/T_s), \tag{2}$$

where the single-sided bandwidth is $1/2T_s$ Hertz. When using a Nyquist pulse, the data can be detected by sampling at multiples of the symbol duration [30]. Fig. 1(a) and (b) show how the baseband signal spreads in time and frequency domains.

Usually, signal shaping is applied to the sinc-function. A factor, e.g. $\frac{T_s^2}{T_s^2-4\alpha^2 t^2}\cos(\frac{\alpha\pi t}{T_s})$, can be multiplied by (2) leading to a trapezoidal pulse shape in time domain and bandwidth of $\frac{1+\alpha}{2T_s}$ Hertz. α is called the excess bandwidth factor. There are schemes to make the bandwidth narrower than the Nyquist pulse which is out of the scope of this paper [31], [32], [33].

In wireless transmission schemes, baseband signals are transformed to higher frequencies. Fig. 1(c) shows the frequency bands normally used in COM and PE, respectively. Based on (1), the baseband pulse train can be multiplied by a carrier as follows:

$$s(t) = \sqrt{2E_s}\sum_n a_n\, p(t - nT_s)\cos(\omega_s t), \tag{3}$$

where $\omega_s = 2\pi f_s$ is the carrier frequency. The modulated signal for a Nyquist pulse is shown in Fig. 2(a). COM modulation shifts the center frequency of the baseband pulses from zero to the carrier frequency at $\omega_s = 2\pi f_s$.

B. PE MODULATION

PE converters operate based on rectangular pulses. The main difference with COM is to construct a single frequency signal by superposing many rectangular pulses which have SS in frequency domain. Normally, frequency contents near the desired fundamental frequency are eliminated using superposing of pulses with different widths. Far frequencies are eliminated using low-pass low-order filters, e.g. an LC filter, to preserve high energy conversion efficiency. Any additional frequency contents on the desired frequency, i.e. DC or 50/60 Hz in todays AC grids, are referred as ripples and are limited to a maximum bound by standard and codes such as IEEE Std. 519-1992 and IEEE Std. 519-2014 as well as European standards IEC 61000-2-2 and IEC 61000-2-4.

Fig. 2(b) shows the Sinusoidal PWM (SPWM) for generating an AC reference signal in a PE converter converting energy from DC to AC. As it can be seen, the undesired frequencies are eliminated as a function of the modulator

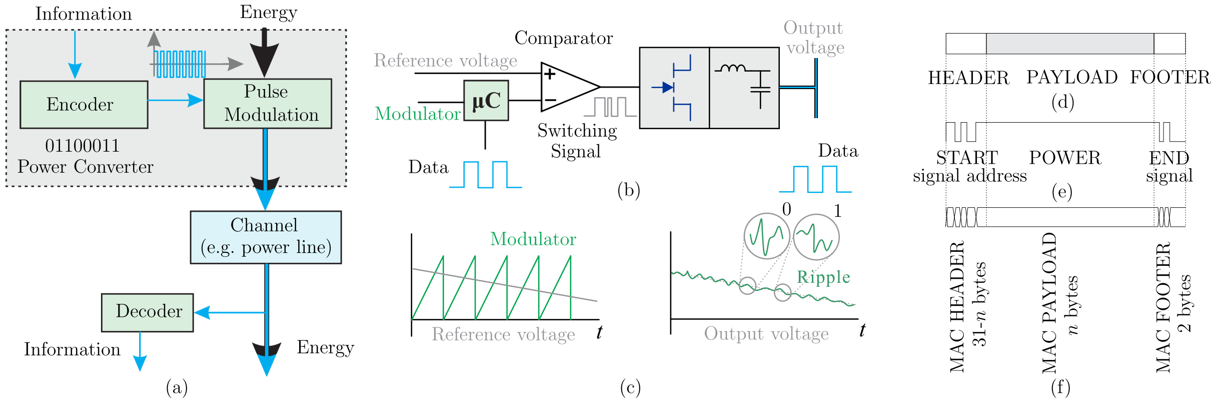

FIGURE 3. TPC concept: (a) schematic representation, (b) hardware implementation, (c) data is encoded as power ripple, (d) general structure of data and power packet protocols, (e) conventional power packet structure [34], and (f) data packet structure based on [35].

frequency f_0 and carrier frequency f_{sw} ratio. A detailed discussion of conventional PWM for PE can be found in [36] as well as SS-based PWM in [37]. Due to the limitation of physical semiconductors and other passive components, in particular limited switching frequency due to increased power losses and break-down voltage limits, different modulation schemes have emerged in power electronics. Moreover, diverse applications from low-power to high-power applications have let to enormous power converter topologies. A quick survey of the topologies can be found in [38], [39].

C. TALKATIVE POWER CONVERSION

It is shown in [4] that ripples originating from the switching functions of power converters can be used for data transmission. This finding can be further extended without violating the grid codes and standard requirements for Total Harmonic Distortion (THD) criteria. COM can be integrated into the PE converter software providing simultaneous information and energy transfer which is called talkative power [8], [18]. The TP concept is represented in Fig. 3(a), schematically. Fig. 3(b) and (c) show how data can be encoded into modulation and then it appears as switching ripples. In this figure, the voltage ripple is magnified to illustrate the concept, practically.

The SNR is defined as the ratio of signal power to noise power [18]. The SNR must exceed a certain threshold value in order to guarantee an acceptable bit error rate. Since the ripple voltage is the useful signal, the signal power is the average power of the ripple signal. Because the ripple should be as small as possible from a power quality point of view, a trade-off between PE constraints and COM requirements exists. Channel coding is a suitable technique for reducing signal power while still achieving an acceptable bit error rate [18].

D. DATA PACKET STRUCTURES FOR TPC

The general structure of a data packet is shown in Fig. 3(d). The data contents of the header, payload, and footer could vary depending on the level of security as well as the used communication protocol. It has been shown that power packets in the power grids can be conceived as data packets. In [40], the concept of digital grid is introduced where the main grid is divided to smaller μ-grids which operate asynchronously. The power converters are defined as grid routers and an IP address is given to each converter using conventional PLC. A more general and comprehensive power packet has been proposed in [34], [41] where a power packet is directly generated using a switch matrix. Time-Division Multiplex (TDM) is used to avoid mixing the power packets even in the same line. This power packet structure is shown in Fig. 3(e). Most of the research in this context is at system level [42], [43], [44], [45], [46]. This prior art provides a good insight about how power can be augmented with data, called energy packets. However, these energy packets are fundamentally different from the TPC concept. The first category uses PLC in addition to power conversion and the second category uses the switch matrix only for TDM. Moreover, the data packet structure is more complicated than the conventional structure that has been elaborated in these conventional power packets as shown in Fig. 3(f). TPC has no limitation on the data packet structure, as long as it is not used in delay sensitive applications. In low latency applications, both modulation scheme and data packet structure must be selected considering the limitations. Worth mentioning are [47], [48], where combined data and energy packets are directly generated using a PE converter. Hence, these two references are instances of TPC.

III. TPC MODULATIONS

A classification of TPC is given in Fig. 4. TPC can be divided into RS-TPC and CS-TPC as shown in Fig. 4(a) and (b) [14], [15], and hybrid combinations thereof [12]. RS-TPC embeds information via superposition of data on the reference voltage, while CS-TPC modifies the carrier signal for this purpose. RS-TPC and CS-TPC resemble the operation of a conventional PLC modem [49] but without coupler hardware. Signals are modulated by shifting the carrier frequency (e.g., PWM-FSK) and/or phase (e.g., PWM-PSK, and PWM-PPM),

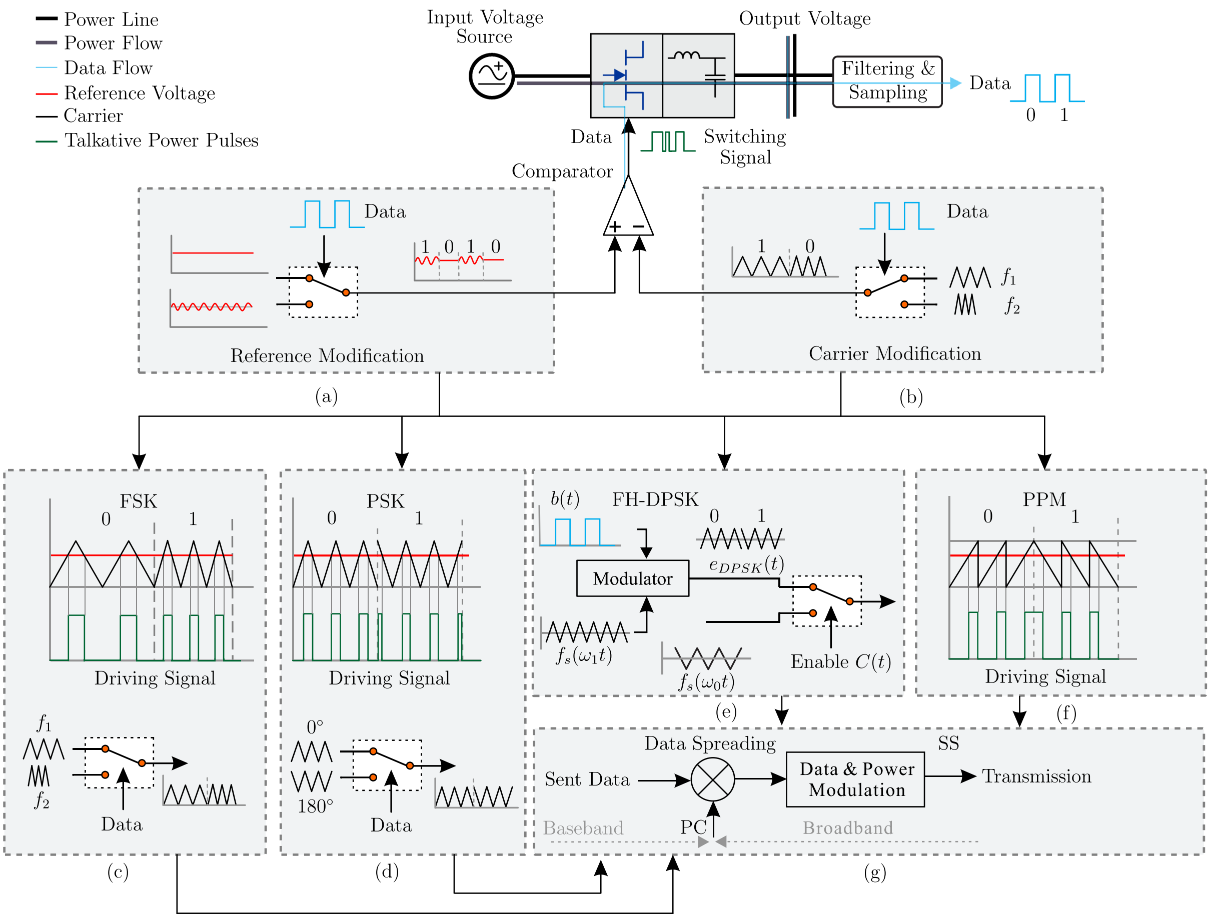

FIGURE 4. Classification of TPC: (a) modifying the reference modulator for superposing data, (b) modifying the carrier to embedding data, (c) schematic and implementation mechanism of PWM-FSK [21], (d) schematic and implementation of PWM-PSK [21], (e) principles of PWM-FH-DPSK [17], (f) waveforms of the data and switching function of PPM [18], and (g) block diagram of the DSSS-based PWM strategy [19].

as well as combinations thereof such as PWM-FH-DPSK [8]. Commonly, one binary digit (i.e. one bit) is transmitted in multiple carrier periods for improved demodulation performance, which limits the transmission rate. Recently, channel coding has been proposed to avoid signaling using multiple carrier periods [18]. Besides, many modulation schemes can be combined with SS communication to enhance the robustness against interference, and configure multi-user access via CDMA [19].

A. PWM-FSK

The PWM-FSK modulation schematic is shown in Fig. 4(c). The TPC functionality is enabled by changing the switching frequency [4], [18], [21]. The converter operates at frequency f_1 when transmitting bit "0," while it works at frequency f_2 when transmitting bit "1". Hence, the duty-cycle of the driving pulse can remain constant and meanwhile the data are embedded into the pulse's frequency. Based on this, the COM signal can be demodulated via the sliding Fast Fourier Transform (FFT) algorithm, and the length of the sliding window equals the period of one bit.

It is noticeable that the variation of switching frequency will cause data-dependent ripple fluctuations in TP converters and as a consequence, PWM-FSK results in power quality issues from a power system point of view.

B. PWM-PSK

A schematic diagram of PWM-PSK is shown in Fig. 4(d). Given a fixed carrier frequency, the carrier phase angle is a degree of freedom for PWM-PSK to modulate data [8], [21]. A phase angle of 0° represents bit "0," while the 180° represents bit "1". By changing the phase of triangle carriers, multi-level PSK can also be realized as the phase plane is divided into multiple sectors.

As compared to PWM-FSK, PWM-PSK can maintain a constant switching frequency, avoiding power quality issues caused by the switching frequency variation.

C. PWM-FH-DPSK

Multi-TP-converters can be mutually interfered at their operating frequencies, distorting the communication and deteriorating the SNR. Thus, PWM-FH-DPSK was proposed in [8]

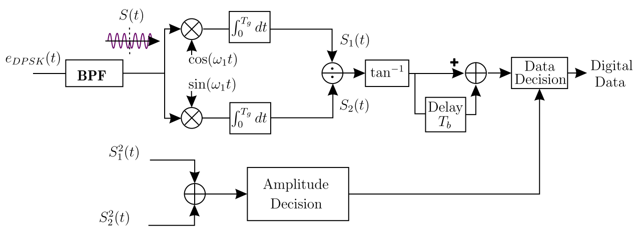

FIGURE 5. Demodulation process of PWM-FH-DPSK [17].

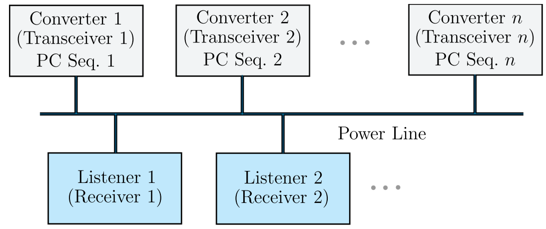

FIGURE 6. CDMA concept for a system with multiple converters [19].

and [17]. The modulation signals of DPSK and the demodulation process are detailed in Figs. 4(e) and 5, respectively.

A data transmission enabling signal $C(t)$ is employed to select the carrier frequency. When the converter does not transmit data, $f_s(\omega_0 t)$ is chosen, otherwise, the modulated carrier $e_{DPSK}(t)$, baseband data $b(t)$, and carrier $f_s(\omega_1 t)$ are chosen to send data. This method enables the converter to communicate in DC grids with multiple converters and provides a high band utilization. The coherent demodulation process is illustrated in Fig. 5. After the received signal passes a bandpass filter, signal $s(t)$ can be regarded as a sinusoidal wave. If the two frequencies are orthogonal, implying that the integration of their products within a demodulation window equals zero, the phase can be calculated, and the digital data can be derived by subtracting the previous phase from the current one.

D. PWM-PPM

In PPM, data symbols determine the pulse position [18]. Power determines the width of the pulse. Thereby, it leads to TPC. The basic data sequence and switching functions of PWM-PPM are shown in Fig. 4(f). In PWM-PPM, logical "0" and "1" are related to falling and rising edges as shown in the figure. PWM-PPM maintains a constant switching frequency, guaranteeing good power quality.

E. PWM-SS

PWM-SS has been employed to enhance the system's robustness and communication quality [19]. PWM-based TPC methods can be combined with SS communication. The direct sequence SS based modulation principle is shown in Fig. 4(g). The baseband data spread is multiplied by a Pseudorandom Code (PC) for data spreading. The data and power modulation can be realized using aforementioned PWM techniques. Via data despreading with the PC, the data can be extracted. Since a system with multiple converters should configure multiplexing accesses, the distinctive PCs are assigned to each converter. Then, multi-directional TP can be realized via Code Division Multiplexing Access (CDMA), whose concept for a system with multiple converters is shown in Fig. 6.

IV. TPC IN DIVERSE CONVERTERS

TP converters can be mainly divided into DC/DC and DC/AC converters based on their output. Regarding the TP converters' topology, namely, whether the transformer is available, DC/DC TP converters can be mainly categorized into non-isolated or transformerless converters and isolated converters, in which the full-bridge topology is widely employed. TPC in diverse PE converters is detailed as follows.

A. NON-ISOLATED DC/DC TP CONVERTERS

The DC bus is a common channel for power and data transmission, and the TP converters are connected in parallel to the DC bus. With respect to the power flow, the functions of TP converters are divided into load splitting and source splitting, corresponding to load-side TPC and source-side TPC, respectively. To achieve reliable COM, the ripple should be robust against interference, but for some PE topologies, the ripple at the bus side wobbles drastically with the variation of input voltage or load, decreasing the PLC system's robustness. Therefore, the operating conditions of each DC/DC topology should be assessed. The applicability of different topologies in source and load-side TPC, which instructs the design for PLC among multiple non-isolated converters, has been detailed in [21].

B. SINGLE ACTIVE FULL-BRIDGE-BASED TP CONVERTERS

Implementation of a talkative full-bridge converters is schematically shown in Fig. 7(a) and (b). Both PWM-FSK and PWM-PSK can be employed in full-bridge converters. Here, PWM-PSK is preferred for obtaining good power quality.

The relative phase ($\varphi_A - \varphi_B$) between the leading leg and lagging leg is determined by power control, which cannot be changed during communication, but the common phase $\varphi_A + \varphi_B$ is a decoupled control freedom, which can be modulated to embed signals.

In [23], a bipolar phase shift modulation was used to ensure the average current constant. As shown in Fig. 7(c), bit "1" is represented by triangle carriers with alternative shifting phase $+\Delta\varphi$ and $-\Delta\varphi$ while bit "0" is represented by carriers without phase shifting. Due to the phase shifting, the gate signals S_1 and S_3 are shifted with a positive time $+\Delta t$ and negative time $-\Delta t$ successively when transmitting bit "1," flexibly changing the amplitude of inductor current and output power, and providing an intensity-controllable approach to adapt complex operating environments.

C. THREE-PHASE AC/DC TPC

As early as 2010, many studies on PLC in inverter-fed motor systems have been carried out, and most of them developed

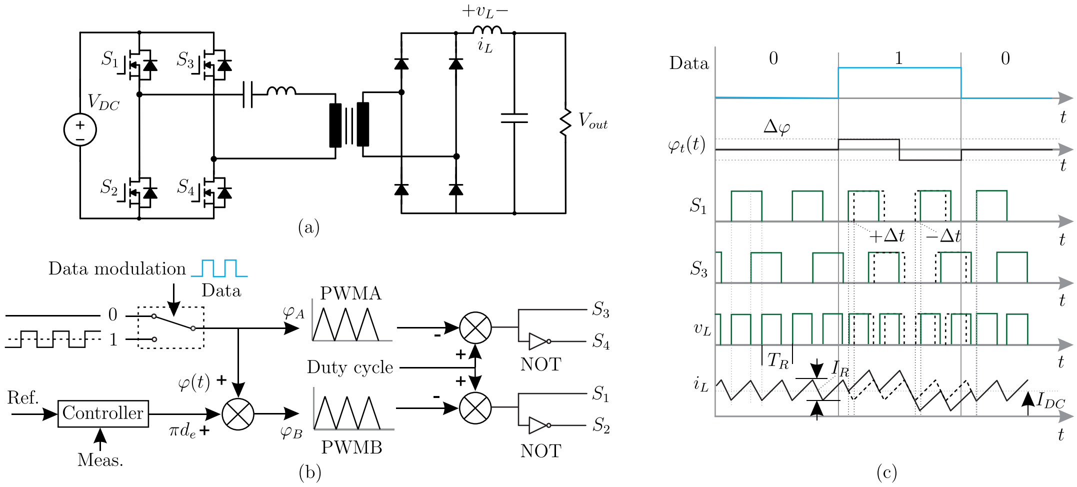

FIGURE 7. Full-bridge TP converter [23]: (a) schematic circuit, (b) power and data modulation process, (c) bipolar PSK waveforms.

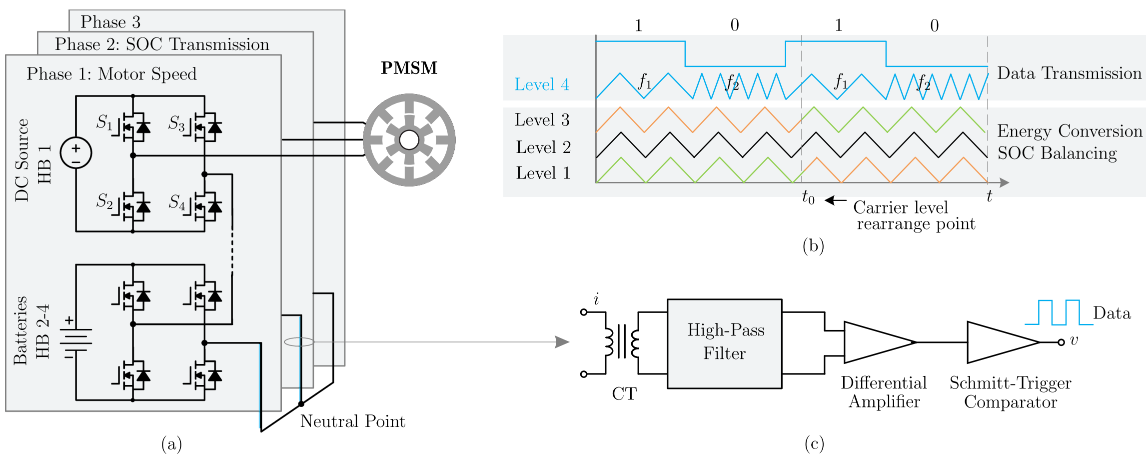

FIGURE 8. CHB-TPC for EV applications [10]: (a) schematic circuit, (b) FSK-based level-shifting PWM TP modulation for CHB-TPC, and (c) an example receiver, proposed in [50], for sampling high frequency data signals superimposing the current.

communication and energy harvesting on motor cable via coupling interface and PLC modem [51], [52]. In this system, high-bit-rate communication relies on high-frequency sinusoidal carriers injected into the cable, which leads to high-frequency noise and torque ripples. By contrast, TP in AC/DC converters can be employed widely besides motor cable scenarios, exempting the coupler's design and maintenance. Nevertheless, little research relating to coupler-less communication in a three-phase AC/DC converter has been conducted.

Recently, a power and data composite modulation strategy for a three-phase Voltage Source Inverter (VSI) system was proposed [53]. This method borrows the concept from RS-TPC and PWM-2FSK in DC/DC converters and can switch to those two FSK modulations separately. Meanwhile, the small-signal model of the VSI with the superimposed information-carrying signal is built and its stability is analyzed and guaranteed under the selected parameters when communicating.

D. CASCADED H-BRIDGE TPC

Cascaded H-Bridge (CHB) converters might be an interesting solution for EV charging, battery packs, and smart transformer applications by reducing the required stages of energy conversion in medium voltage systems [54], [55]. To further improve the degree of optimization in CHB-based EVs, TPC is employed for motor speed control and battery State of Charge (SOC) balancing at a maximum data rate of 600 b/s [10], which is called CHB-TPC in this paper. There are four H-Bridges (HBs) in each phase, where one of them is connected to a DC source and responsible for the data signal generation and the rest are connected to batteries as in Fig. 8(a). FSK-based level-shifted PWM has been applied to a converter for achieving TP modulation. FSK is only applied to HB 1 as shown in Fig. 8(b). The resultant modulation influences the phase current waveform due to high order frequency components. Such data can be recovered easily by sampling the phase current as it has been designed in [50].

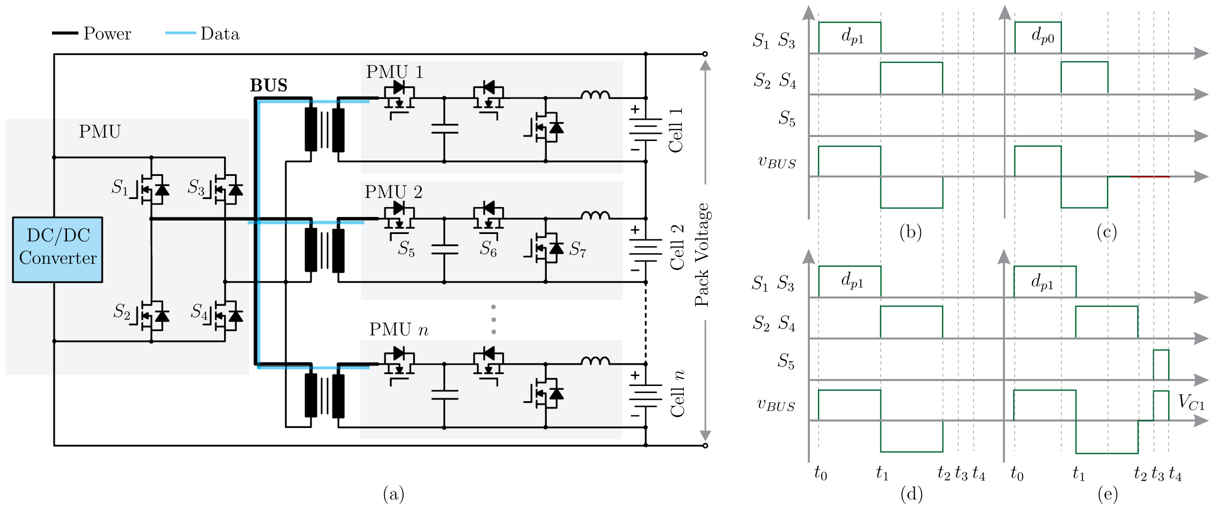

FIGURE 9. BMS employing the TP concept [24]: (a) schematic of the circuit topology, (b) generation of logical "1" in PMU, (c) generation of logical "0" in PMU, (d) generation of logical "1" in CMU, (e) generation of logical "0" in CMU.

CHB-TP-converters presented in [10] and [50] have not been completely researched in terms of data handling capacity. CHB could generate more levels enabling TPC with an M-ary alphabet, where M is the number of levels.

V. APPLICATIONS OF TPC

Potential application scenarios of TPC in both wired and wireless systems are detailed as follows.

A. BMS

The topology of a BMS is shown in Fig. 9. The battery pack is equipped with a Pack Management Unit (PMU) at the primary side of isolation transformers, and each cell is controlled by a Cell Management Unit (CMU) at the secondary side of transformers. The topology of a PMU contains two full-bridge converters, one used for DC/DC conversion and another used for DC/AC inversion while the topology of a CMU contains a half-wave rectifier and a bidirectional equalizer circuit. PMU and CMU measure the pack and cells' voltage, current, surface temperature, and the SOC, which are key indicators for regulating packs and cells. Hence, TPC among the converters in PMU and CMU can facilitate battery management.

In [24], the bidirectional data exchange among PMUs and CMUs was realized via TDMA. The period of a transmission cycle was divided into four slots from t_0 to t_4, the power slot, recovery slot, idle slot, and signal slot. The power slot is for power transmission and also for PMUs to send data, while a signal slot is for CMUs to send data. PMU supplies positive voltage in the power slot and generates a negative voltage in the recovery slot to reset the magnetizing current of the transformer in every CMU. The idle slot is inserted between the recovery slot and signal slot, which guarantees the magnetizing current recovers to zero. In the power slot from t_0 to t_1, PMU transmits data to CMUs by changing the duty cycle, as shown in Fig. 9(b) and (c), where duty cycles

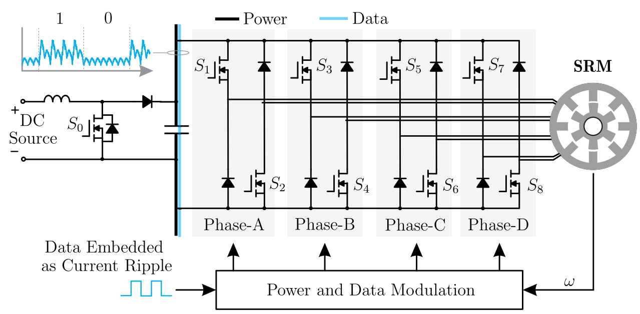

FIGURE 10. TPC in SRM-based system [26].

d_{p1} and d_{p0} represent bits "1" and "0," respectively. During the signal period from t_3 to t_4, CMUs send out data by changing the on/off states of the rectifier switch S_5, which determines the bus voltage which is depicted in Fig. 9(d) and (e), respectively. When CMUs send bit "1" to PMUs, the power switch S_5 remains off, and the bus voltage keeps zero. When sending bit "0," S_5 is turned on, clamping the bus voltage to V'_{C1}, which equals V_{C1}/nT, where V_{C1} is the voltage of capacitor C_1 and nT is the ratio of the transformer. Hence, PMU and CMU transmit data in different time slots, achieving bidirectional communication.

B. SWITCHING RELUCTANCE MOTORS/GENERATORS

TPC has also been applied to electric drive systems [3], [25], [26]. As shown in Fig. 10, a Switching Reluctance Motor (SRM)-based energy conversion system is split into the source side and load side, where an 8/6 (stator/rotor) SRM is controlled by eight switches of the asymmetrical half-bridge converter. By regulating the turn-off angle of the SRM converter to embed signals with specific frequencies, which can be the feature for demodulation, the COM signals can be detected at the power supply side, and

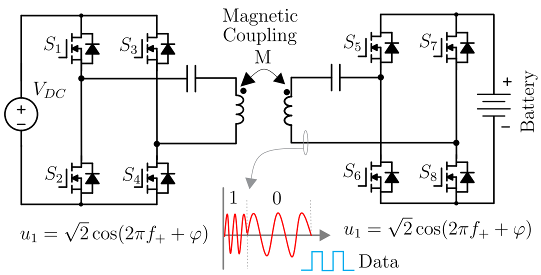

FIGURE 11. TPC in wireless battery charging with FSK modulation [56].

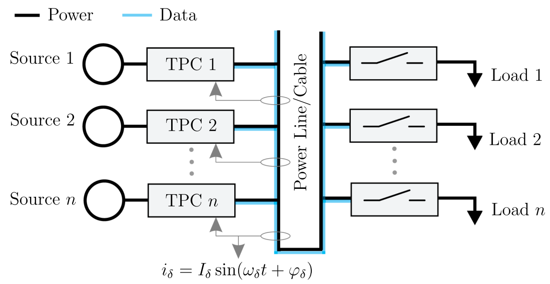

FIGURE 12. RS-TPC enabled μ-grid [59].

demodulated via the Auto-Regressive Power Spectrum Density (AR-PSD) method. The AR-PSD method considers the estimated values outside the demodulated time window random, thereby obtaining a higher resolution than traditional FFT. Because the asymmetrical half-bridge converter receives power with information ripples from the DC bus, expected data can be received by demodulating signals on the source side.

C. WIRELESS EV CHARGING

An overview of SWIPT in EV charging application has be provided in [57] where the classification has been done based on the link and the carrier. TPC has been applied to wireless EV charging, as shown in Fig. 11, in [56]. FSK is designed for cosine carriers signals in the vicinity of the magnetic resonance frequency achieving OFDM. Electric vehicles can communicate with charging stations via the bidirectional PLC, thus optimizing the charging process and bringing convenience for EV owners.

D. μ-GRIDS

Standalone small μ-grids in isolated areas could benefit from TPC as a low bandwidth COM [58]. TPC enables decentralized and autonomous control strategies leading to optimal resource allocation, load shedding and reconfiguration.

In [59], RS-TPC has been realized using three-phase converters to enable communication between different converters and energy sources in the μ-grid and to share their energy in an optimal manner. The proposed RS-TPC injects an AC voltage into the shared line using the voltage reference $v_{ref}^{TPC} = v_{ref}^{CC} + V_\delta \sin(\omega_\delta t)$ where v_{ref}^{CC}, V_δ, and ω_δ are voltage from the current controller, TPC voltage amplitude and frequency, respectively. Fig. 12 shows the μ-grid enabled by TPC. The proposed method uses reference superposition therefore at higher ω_δ frequencies it might lead to stability problems. The proposed strategy is useful for very small standalone μ-grids. Further methods are needed to achieve a generalized TPC for an μ-grids with arbitrary topology.

VI. FUTURE PERSPECTIVE OF TPC

COM plays a key role in many centralized and decentralized systems where the system components need information from each other to operate or to be optimized. Significant literature can be found where power and data are transmitted simultaneously not only for electrical energy grids but also for low-power and Ultra Low-Power (ULP) electronics. Until now, TPC has not been considered in a common framework. In the next subsections, the power and data transfer, obeying Maxwell's equation, are classified and future applications are contemplated.

A. TPC CLASSIFICATION

TPC can be briefly classified based on different channel types covering both PLC and SWIPT technologies. Power and data can be transmitted in wireless and/or wireline channels:

- Wireline: Nowadays, the bulk power in electric grids is transmitted using copper or aluminum conductive channels. Electrical signal are delivered at low frequency in high conductivity medium resulting in high efficiency as well as long distances up to hundreds of kilometers. Another well-known channel, which is commonly used in communication, is optical fiber. Optical fiber is non-conductive and it works based on electromagnetic field propagation.
- Wireless: Wireless Power Transfer (WPT) can be divided to near-field, mid-field, and far-field based on the wavelength (λ), sender-receiver distance (r), and device largest dimension, (D) [60], [61]. Near-field is respected to the distances where $r_{NF} \leq 0.62\sqrt{\lambda^{-1}D^3}$. Mid-field range is defined as $0.62\sqrt{\lambda^{-1}D^3} \leq r_{MF} \leq 2\lambda^{-1}D^2$. If $r_{FF} \geq 2\lambda^{-1}D^2$ then WPT is called far-field. Near-field wireless power transfer can be further divided to inductive, magnetic resonant, and capacitive power transfer [62]. In the mid-field, both magnetic and electromagnetic fields transfer power and data. Far-field conveys power through electromagnetic fields where microwaves and laser beams have been extensively used for power delivery [63], [64], [65], [66].

Fig. 13 shows qualitatively the frequency and distance of power and data transfer in TP as well as their classification. The energy convey methods which do not obey Maxwell's Equations are out of the scope of this paper, e.g. acoustic energy transfer etc [67].

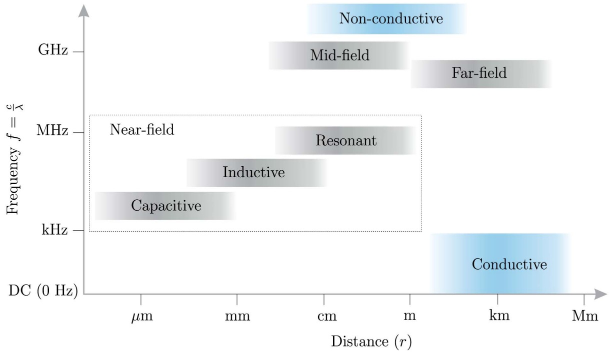

FIGURE 13. Qualitative comparison of wireless and wireline power transfer in terms of distance and frequency.

B. PROSPECTIVE APPLICATIONS OF TPC

TPC concept sheds the light on new applications. Following items can be highlighted for future applications of TPC:

- *Talkative μ-grids:* decentralized μ-grids could benefit significantly from TPC without the need for additional parallel communication infrastructure. The information from different energy sources, loads, and storage can be shared on the grid and therefore the power flow within the grid can be controlled optimally. It is in particular can enable μ-grids interfaced to main grid by a Smart Transformer (ST) [68].
- *Talkative e-Transportation:* electrical traction systems [69], electric vehicles, electric buses, and electric heavy duty trucks are the core of future carbon free transportation [70]. Moreover, maritime transportation [71] and aircrafts [72], [73] are not exempted from electrification. All these electrified vehicles might use power electronics either for their own standalone operation or for connection to a grid to exchange energy. In standalone mode, power electronic converters interconnect the loads, electric machines, and batteries or fuel cells [74]. Therefore, TPC can reduce the volume and weight at least related to communication system of the e-Transportation systems.
- *Near-field TPC:* Wireless charging, in particular EV charging, is the most dominant near-field application based on the literature. US department of energy has announced that a data rate of 100kbps is required for home users of EV charging [75]. Normally, wireless communication is employed besides WPT [76] which has a much higher bandwidth [77]. The control of the wireless EV charging system is also possible without any dedicated wireless communication system [78], [79] by compromising the closed-loop control requirements. Conventional PLC can be utilized at the cost of additional communication modem [80]. Differently than these methods, TPC has been adopted for EV charging [81] demonstrating a data rate of 64 kbps without any additional communication instruments. It is shown in [56] that using FSK, a data rate about 300 kbps can be achieved at a resonant frequency of 1 MHz. Since TPC is capable of guaranteeing EV charging requirements, it can greatly reduce the converter volume as well as the weight of required copper and insulation material for the EV plug. In addition to charging applications, near/mid-field TPC can be also used for powering medical implants, in particular using magnetic resonant coupling [82], [83]. Battery-free wearable sensors have been enabled by this technology where data and power can be exchanged between sensors easily in near-field [84]. The reduced size of implants achieved by simultaneous power and data transmission is a clear advantage of TP in such applications [84], [85].
- *Far-field TPC:* The paradigm shift toward unifying energy and information transmission at far-field has been coined out in [86]. Authors of [87] have contemplated the applications of wireless far-field energy transmission. The wireless infrastructure might also radiate energy to power up billions of low-power devices and Ultra Low-Power (ULP) devices [61], [88], [89], [90], [91], [92]. Moreover, it can eliminate the need for batteries in some mobile applications [92] eliminating the need for additional power supply devices. Hence, this concept can be classified as a sort of TPC. The focus of far-field TPC is on harvesting energy using rectennas from the existing radiate energy [93], [94]. However, further attentions are needed in the high-power far-field transmitter design and development. Especially, a switching mode power amplifier might increase the efficiency of conversion drastically [95].
- *Visible Light TPC:* Visible Light Communication (VLC) is supposed to solve some of the conventional Radio Frequency (RF) communication drawbacks such as vulnerability to interference and bandwidth limitation [96]. Usually, a converter serves as the signal modulator while its load is replaced with a high-brightness Light Emitting Diode (LED), and the receiver demodulates signals via a photo-detector and conditioning circuits. In the VLC scenario, the information transmission is performed by modulating the light intensity waveform emitted by the high brightness LEDs. To fulfill the both the lighting and the communication tasks, LED current is made up of a DC component that establishes the lighting level and a high-frequency AC component that cannot be seen by human eyes and is determined by the modulation scheme [28]. A comprehensive review of VLC-LED drivers and modulators types has been presented in [97]. Both linear and switching mode modulator circuits have been discussed. The work highlights a trend toward switching modulators due to higher efficiency and higher power levels. This indicates that TPC can be easily embedded in the physical layer of VLC-LEDs. Crystalline silicon photovoltaic cells have been used not only for solar energy harvesting but also as a receiver of VLC modulated signals in [98]. The presented concept sheds a light on the possibility of visible light TPC achieving

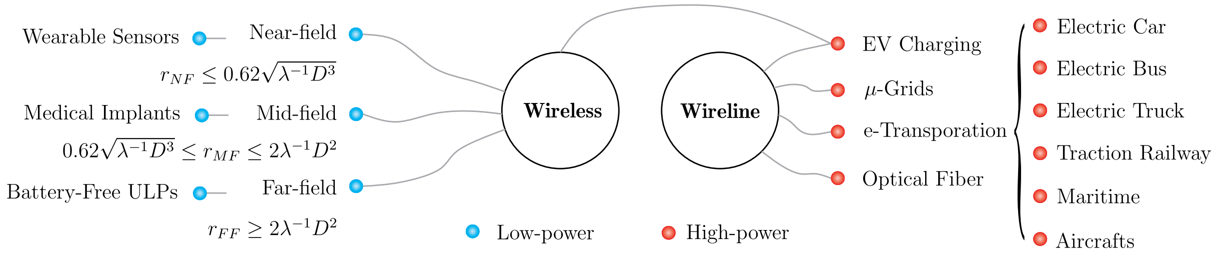

FIGURE 14. Diagram of the prospective applications of TPC respect to main function of the devices.

more than 11 Mbps data rate while operating as a photovoltaic energy source.

- *TPC over Optical Fiber:* Transmission of power in addition to data over the same optical fiber is not new and it dates back to two decades ago when power is delivered using the optical fiber medium to eliminate the need for external power supplies [99]. The core cross-section size of the optical fiber is the main barrier to deliver high-power. A double-clad optical fiber structure has been proposed in [100], [101] to overcome the drawbacks of conventional cores in handling power. Successful delivery of 30 W power using a 1.3 μm-band (wavelength cut-off) double-clad optical fiber for 300 m has been shown in [102]. More over, 40 Watt and 150 Watt power transmission has been respectively achieved in [103] and [104] based on this double-clad optical fiber geometry. Maximum distance 1 km of power transmission over optical fiber has been reported in [105]. The applicability of power transmission over optical fiber has been demonstrated in applications such as remote antenna units [106], [107]. Despite the long history of transmission of power and information simultaneously through optical fibers, there is a limited literature on the topic. Introducing TPC over optical fibers might create a solid foundation for this new niches of technology.

Fig. 14 represents the prospective applications of TPC in different energy disciplines. TP not only promises reduced components count and higher compactness but also paves the way and contemplates new solutions for traditional complicated systems where power and energy are inseparable parts. The far-field talkative-powered devices could communicate, compute and sense surrounding environment without the need for energy storage and its management unit resulting in very compact designs. Similarly, it could lead to the reduced component count and the power density without violating the conversion efficiency. Power converters and submodules could operate autonomous enabling new control modes that are impossible by conventional communication techniques.

VII. CONCLUSION

In this paper, Talkative Power Conversion (TPC) technologies are reviewed and its application to Power Line Communication (PLC) and wireless communication are addressed. TPC is classified as Reference-Signal-based TPC (RS-TPC) and Carrier-Signal-based TPC (CS-TPC). The combined modulations of CS-TPC with Pulse Width Modulation (PWM) are explained and compared. The applicability of TPC-based non-isolated DC/DC converters, isolated single active full-bridge, three-phase, and cascaded H-bridge converters are detailed. Emerging practical field applications of TPC are comprehensively analyzed, including battery management systems, wireless EV charging stations, switching reluctance motors/generators, and μ-grids. The future applications of the TPC concept are contemplated not only for power electronics and electric grids but also for low power and ultra low power electronics whenever the switching function of semiconductors can lead to energy conversion and/or information generation. TPC is extended to far-field, optical fibers, and visible light communication.

An in-depth comparison between RS-TPC and CS-TPC with respect to system stability, dynamic response, latency, and data rate is subject to future work.

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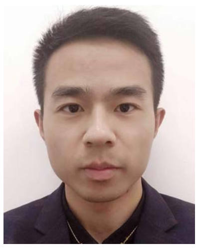

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