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LCL FILTER WITH CASCADED MULTILEVEL INVERTER BASED POWER AND SIGNAL MULTIPLEX TRANSMISSION FOR ELECTRIC VEHICLES

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Abstract—Power & signal multiplex transmission (P&SMT) is a technique that uses power electronic circuits for communication signal transmission. In this paper, a three-phase cascaded multilevel inverter-based P&S MT system with LCL filter is proposed. The proposed method can transmit communication signals without using a Controller Area Network bus, thereby reducing the wiring cost of the conventional electric vehicle (EV) communication system and reduced hormonics. The designed system can achieve motor speed regulation and battery balance discharging for EVs. With the combined pulse width modulation scheme, LCL filter and frequency shift keying method, both power and communication signals are transmitted successfully in a simulation model implemented in Matlab/Simulink.

I.INTRODUCTION

THE challenges posed by climate change are spurring experts and researchers to investigate the alternatives for fossil fuels to achieve carbon dioxide emissions reduction. Nowadays, the application of electric vehicles provides a feasible solution for energy saving and emission reduction in the automotive industry. Compared to the traditional internal combustion engine cars, electric vehicles (EVs) not only produce fewer air pollutants such as CO and NOx, but also generate less noise [1], [2]. Furthermore, if the battery of EV is charged at night, it can avoid the peak of power consumption, which is beneficial to the grid to balance the load and reduce the cost [3]. Since various subsystems such as the motor control unit (MCU) and the battery management system (BMS) in an EV require communication with the transmission control unit (TCU), it is necessary to employ an effective method to realize signals transmission [4], [5]. One of the approaches that is widely accepted by manufacturers and researchers for data transmission in EV is through a Controller Area Network (CAN) bus because of its high reliability and high communication baud rate [6], [7].

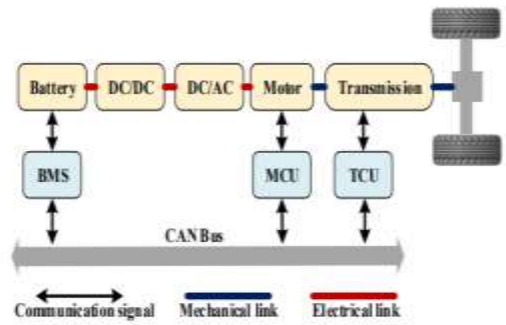

Fig. 1. The general powertrain structure of an EV

The general powertrain structure of an EV is exhibited in Fig.1. Some conventional power systems for EVs employ a DC/DC converter to boost the battery voltage for a 2-level inverter [8], [9]. This approach can have a high voltage change rates (dV/dt), which leads to high switching losses [8]. Moreover, such the system is expensive and has low power density because of the utilized bulky inductors for the DC/DC boost converters [9]. Although the traditional EVs realize their internal communication through the CAN bus, the communication channel and the power transmission line are still two independent sections, and the whole system can still be optimized.

This paper proposes a power & signal multiplex transmission (P&SMT) method to transmit both power and communication signals through a three-phase multilevel inverter circuit for EVs. The individual devices of the multilevel inverter have a much lower switching losses than that of a 2-level inverter, and a DC/DC converter is not required since the cascaded multilevel inverter itself can boost the battery voltage. In the proposed system, the power conversion is realized by the pulse width modulation (PWM) method, and the transmitted signals are modulated by the frequency shift keying (FSK) approach. Instead of using a CAN bus as a communication channel in the up-to-date EVs, the proposed approach can greatly reduce the expenditure on the communication system because the power and signals are transmitted simultaneously through the same power line.

II.LITERATURE REVIEW

There are several power and signal transmission methods that have been applied in various areas. For example, the general method for

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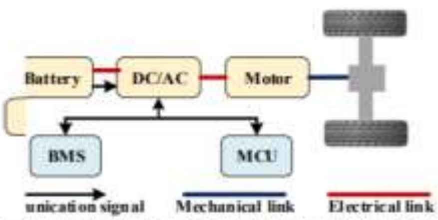
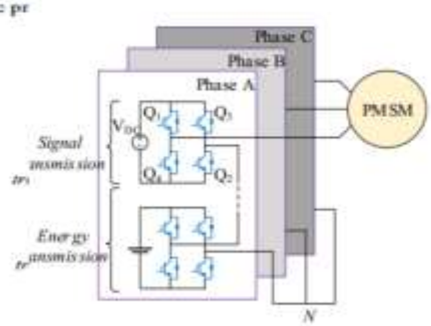
transmitting data through a power line is to modulate the data onto a high-frequency carrier, and then couple the data to the power line through a coupling circuit after power amplification [10]. Since the power line itself is not designed to transmit communication data, adding signals on it can increase the complexity of the power line channel. Additionally, the electromagnetic interference should be considered while designing a broadband power line communication (PLC) model as its 2 MHz to 32 MHz carrier frequency may coincide with the frequency of short-wave radios [11]. Power over Ethernet (PoE) is the technology that uses twisted-pair Ethernet cabling to pass data along with electric power to some IP-based terminals such as voice-over-Internet telephones and IP camera [12]. However, because the maximum output power of power sourcing equipment of PoE is larger than 15.4W in the standard IEEE802.3af, such technique is not suitable for pan–tilt–zoom camera and other high power required applications [13].



Comm 'ig. 2. The pr oposed system structure of an EV using the P&SMT method.



'ig. 3. Topology of the proposed P&SMT system for EVs.

III.Photovoltaic cell and array modeling

A PV cell is a simple p-n junction diode that converts the irradiation into electricity. Fig.3.2 illustrates a simple equivalent circuit diagram of a PV cell. This model consists of a current source which represents the generated current from PV cell, a diode in parallel with the current source, a shunt resistance, and a series resistance.

IV. INVERTER

An inverter is an electrical device that converts direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits. Static inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers, to large electric utility high-voltage direct current applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar panels or batteries. The electrical inverter is a high-power electronic oscillator. It is so named because early mechanical AC to DC converters were made to work in reverse, and thus were "inverted", to convert DC to AC.

4.1Cascaded H-Bridges inverter

A single-phase structure of an m-level cascaded inverter is illustrated in Figure 4.1. Each separate dc source (SDCS) is connected to a single-phase full-bridge, or H-bridge, inverter. Each inverter level can generate three different voltage outputs, $+V_{dc}$, 0, and $-V_{dc}$ by connecting the dc source to the ac output by different combinations of the four switches, S_1, S_2, S_3, and S_4. To obtain $+V_{dc}$, switches S_1 and S_4 are turned on, whereas $-V_{dc}$ can be obtained by turning on switches S_2 and S_3. By turning on S_1 and S_2 or S_3 and S_4, the output voltage is 0. The ac outputs of each of the different full-bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs. The number of output phase voltage levels m in a cascade inverter is defined by m = 2s+1, where s is the number of separate dc sources. An example phase voltage waveform for an 11-level cascaded H-bridge inverter with 5 SDCSs and 5 full bridges is shown in Figure 4.2. The phase voltage

$$v_{an} = v_{a1} + v_{a2} + v_{a3} + v_{a4} + v_{a5} \quad \ldots(4.1)$$

For a stepped waveform such as the one depicted in Figure 4.2 with s steps, the Fourier Transform for this waveform follows

$$V(\omega t) = \frac{4V_{dc}}{\pi} \sum_n [\cos(n\theta_1) + \cos(n\theta_2) + \cdots + \cos(n\theta_s)] \frac{\sin(n\omega t)}{n}, \; where\; n = 1,3,5,7 \ldots \quad \ldots(4.2)$$

V.PROPOSED POWER AND SIGNAL MULTIPLEX TRANSMISSION

A. System Structure

This paper elaborates the principle of the proposed P&SMT method by using the transmitted battery state of charge (SOC) signal and motor speed control signal as an example. The proposed system structure of an EV using the P&SMT method is shown

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in Fig. 2. The communication between the battery and BMS, and that between the MCU and motor are realized by transmitting signals through a three-phase

$$\left\{\begin{aligned} a_0 &= \frac{2}{T}\int_{-T/2}^{T/2} f(x)\,dx \\ a_n &= \frac{2}{T}\int_{-T/2}^{T/2} f(x)\cos n\omega x\,dx \\ b_n &= \frac{2}{T}\int_{-T/2}^{T/2} f(x)\sin n\omega x\,dx \end{aligned}\right\} \qquad (2)$$

multilevel inverter circuit. The proposed topology of a three-phase P&SMT system is indicated in Fig. 3. Specifically, each phase of the inverter topology contains four series connected H-bridge cells, where the cell powered by a DC voltage source is used for signal transmission, and the rest three cells powered by batteries are applied for energy transmission. The motor speed adjustment signal and the SOC signal are transmitted through the phase A and phase B branch respectively. In this model, a permanent magnet synchronous motor (PMSM) is applied as a load of the inverter topology.

B. Signal Transmission

The signals are modulated by the FSK method in the proposed system and the signal transmission scheme is presented in Fig. 4. If the transmitted 4-bit signal SI is '1010', then two carriers with different frequencies shown in SC can be applied for modulating digital '1' and digital '0' respectively. Since the signal is designed to be transmitted through an H-bridge cell in each phase, such the signal can be modulated by controlling the fast switching process of the four switches in the cell. Specifically, a switch will turn on if a digital '1' is applied as a gate signal and it will turn off when digital '0' is used. In Fig. 3, the switches Q1 and Q2 operate simultaneously

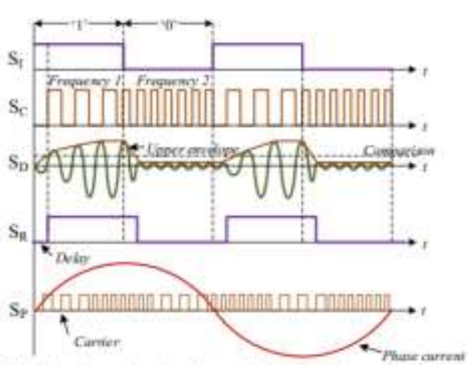

Fig. 4. The signal transmission scheme of the proposed system, where S_I is the initial 4-bit signal '1010'; S_C is the carrier waveform; S_D represents the extracted carrier for digital '1' after using a band-pass filter; S_R shows the restored signal; S_P is the output phase current waveform superimposed with the signal's carrier.

and the switches Q3 and Q4 turn on and turn off at the same time. Besides, the switches Q1 and Q2 operate with the opposite state to that of the switches Q3 and Q4 to avoid short circuit. Because the H-bridge cell used for signal transmission is series connected with the other three cells applied for energy transmission, the transmitted signal can be considered as superimposed on the output current waveform.

Then a band-pass filter is employed to extract the transmitted signal from the output current waveform at receiver. For any signal f(x) with period T and angular frequency ω=2π/T, its Fourier series expansion can be expressed as

$$F(x) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty}\left(a_n \cos n\omega x + b_n \sin n\omega x\right) \qquad (1)$$

where the coefficients ő□, ő□, and ̧□ in this series are defined by Similarly, if a square wave f(t) with period T is applied as a carrier for digital '1', it can be expressed as

$$f(t) = \begin{cases} 0 & -\dfrac{T}{2} \le t < 0 \\ 1 & 0 \le t \le \dfrac{T}{2} \end{cases} \qquad (3)$$

The Fourier series expansion of f (t) is derived as

$$F(t) = \frac{1}{2} + \frac{2}{\pi}\sin x + \frac{2}{3\pi}\sin 3x + \frac{2}{5\pi}\sin 5x + \frac{2}{7\pi}\sin 7x + \ldots + \frac{2}{n\pi}\sin nx \qquad (4)$$

where n is an odd number. Because the Fourier series expansion of f(t) only contains the odd harmonic components, and the first-order harmonic has the largest amplitude, the first-order harmonic can be utilized for restoring the communication signals. For instance, the curve SD in Fig. 4 represents the demodulated carrier for digital '1', then its upper envelope can be acquired using an envelope detector. With an appropriate comparison value, the upper envelope can be recovered to digital '1' when its amplitude larger than the comparison value. Otherwise, it will be recovered to digital '0'. Finally, the restored SR is obtained after sampling the recovered digital signal using the initial bit rate of SI.

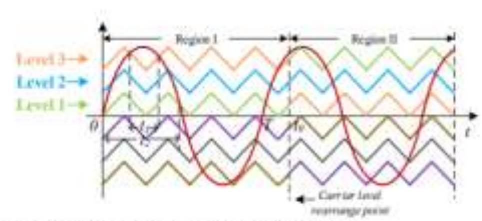

Fig. 5. Carrier level rearrangement in the PWM process.

C. Motor Speed Regulation and Battery Balance Discharging

In the proposed system, the motor speed is managed by setting the power frequency to different values with the transmitted signal. Expressly, the

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relationship among the motor speed n, pole-pair p, and power frequency f for a PMSM is indicated as

$$n = \frac{60f}{p} \tag{5}$$

where the constant 60 refers to 60 s/min. Theoretically, the speed of a 2-pole pair motor should change between 1200 r/min and 1800 r/min if its power frequency varies between 40 Hz and 60 Hz. With the transmitted signal s, the power frequency f is then calculated by

$$f = 20 \times s + 40 \tag{6}$$

The power frequency will be 40 Hz and 60 Hz if the digital '0' and digital '1' occur in the transmitted signal s respectively. Next, the three-phase reference sinusoidal waves are obtained from

$$\begin{cases} P_a = A\sin(2\pi f) \\ P_b = A\sin\left(2\pi f - \frac{2}{3}\pi\right) \\ P_c = A\sin\left(2\pi f - \frac{4}{3}\pi\right) \end{cases} \tag{7}$$

where Pa, Pb, and Pc represent the reference wave in phase A, phase B, and phase C respectively, and A is amplitude. The phase B and phase C reference waves lag the phase A reference wave by 2π/3 and 4π/3 radians respectively. Finally, the modulated variable frequency sine waves are used to drive the motor to achieve motor speed adjustment.

In the conventional sinusoidal PWM method, the gating signal of a switch is generated by comparing the reference wave with a triangular carrier. Because various carriers and the reference wave intersect at different positions, the duty cycle of each switch is different. For instance, in a single period from 0 to T as displayed in Fig. 5, the duty cycle of a switch controlled by 'Level 3' carrier is smaller than that of the other switch modulated by 'Level 1' carrier ($t_1<t_2$) . Since the input power

TABLE I
PARAMETERS VALUE USED IN THE PROPOSED SYSTEM

Parameter name	Value
DC voltage source	30 V
Battery voltage	48 V
PWM carrier frequency	2 kHz
PWM referenced sine wave frequency	40 Hz, 60 Hz
Carrier frequency of motor speed adjustment signal	4 kHz for '1' and 8 kHz for '0'
Carrier frequency of SOC signal	6 kHz for '1' and 10 kHz for '0'

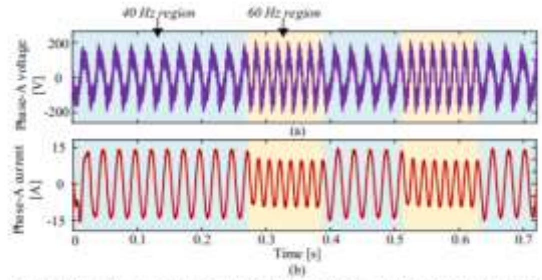

Fig. 6. (a) The output voltage waveform of phase A and (b) the output current waveform of phase A

comes from batteries, the switch operating with a smaller duty cycle consumes less power than the switch operating with a larger duty cycle. This will further lead to the case of batteries' remaining capacity being unbalanced after the system running for a while. Therefore, the battery balance discharging can be realised by periodically rearranging the carrier levels within the PWM process. To achieve this target, firstly, the battery SOC values at the periodical sampling point are combined to form a data stream and transmitted through the DC voltage source powered full-bridge cell using FSK method. After demodulating the signal from the phase current, the SOC values are separated into different decimal numbers. Finally, the carrier levels of PWM are rearranged according to the transmitted SOC values (at t0 in Fig. 5 for example), and the battery balance discharging is realized.

VI.SIMULATION RESULTS

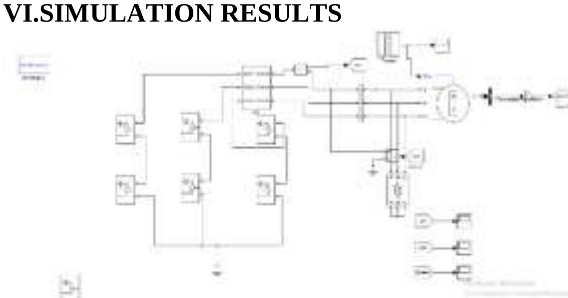

Fig7: Proposed simulation diagram

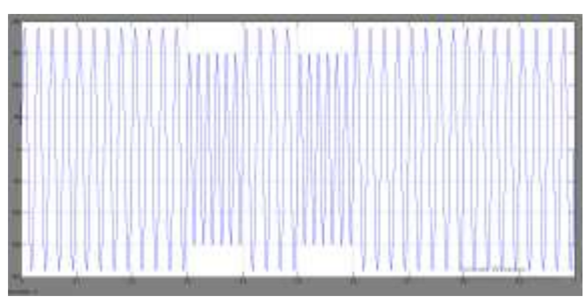

Fig8: Iph

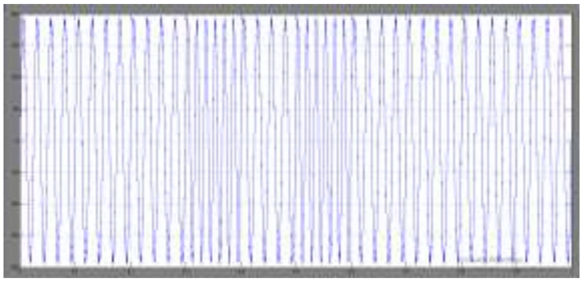
Fig9: Vph

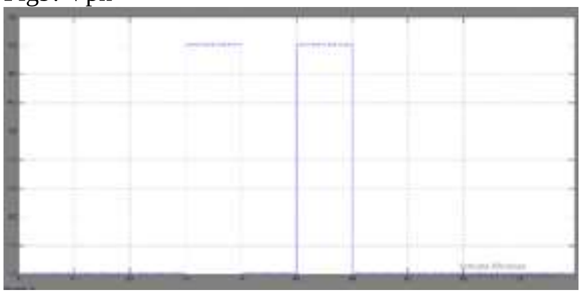
Fig10: Speed

VII.CONCLUSION

In this paper, a three-phase multilevel inverter-based P&SMT system is proposed to achieve motor speed adjustment and battery balance discharging for EVs. Four series-connected H-bridge cells are involved in each phase of the inverter topology, where the PWM controlled three cells are used for energy transmission and the rest FSK controlled cell is applied for communication signal transmission. Since the proposed approach employs a part of the power electronic circuit as a communication channel, the complexity of the entire system can be reduced by simplifying the system wiring. With a simulation model implemented in Matlab/Simulink, the feasibility of the proposed P&SMT method is verified by transmitting the motor speed adjustment signal and the battery SOC signal through phase-A and phase-B currents respectively. Additionally, the signal transmission capability of the proposed method is determined as 600 bit/s after investigating the relationship between the signal bit rate and error rate.

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