

Demonstration of On-road Vehicle Drive with Electric Motor Fed by Power Packets

Shiu Mochiyama

Department of Electrical Engineering
Kyoto University
Kyoto, Japan
ORCID: 0000-0001-7126-9187

Taketsune Nakamura

Department of Electrical Engineering
Kyoto University
Kyoto, Japan
ORCID: 0000-0003-1685-5153

Abstract—The electrification of mobility has led to the concept of connectivity of vehicles in the sense of both information and energy engineering. For the challenge of coordinating such cyber and physical aspects of networked electrified mobility, the authors propose an application of a power packet dispatching system. The power packet dispatching system realizes the integration of delivery and processing of information and power on the physical layer. This paper presents a power-packet-based drive of an electric vehicle. Experimental results of both a bench test and an on-road test support the feasibility of the proposed concept.

Index Terms—power packet, routing, motor drive, electrified mobility

I. INTRODUCTION

Increasing demand for reducing environmental impact is driving the electrification of mobility [1]. One of the paradigm shifts promoted by electrification is connectivity. It is often referred to as Vehicle to X (V2X) concept, where X can be grid (V2G), load (V2L) and other vehicles (V2V), for example. Besides, there also merges the information-centric connectivity with surrounding vehicles and infrastructure to enhance the safety, performance and entertainment aspects of transportation. Under such circumstances, electrified mobilities (E-Mobility) are expected to form a connected system in terms of both information and energy [2].

In such cyber-physical systems [3], the management of information and physical quantities (typically electric power in the case of E-Mobility) are inseparable and dependent largely on each other. Their discrepancy may lead to degradation of performance and, in the worst case, to unexpected failure or damage in the whole connected system.

Recently, the integration of information and electric power engineering has been actively studied [4]–[8]. Among them, we focus on the power packet dispatching system [9]–[11] as a realization of the integrated management of information and electric power. The system deals with electric power supply and demand as a sequence of small fragments called power packets. Power packets are forwarded from a source to a load via a network of power packet routers. As explained later in Sect. II, the time division multiplexing and information tag

attachment on the physical layer ensures the simultaneous delivery and processing of information and power to avoid their discrepancy. This feature gives rise to flexibility in the power management of a connected system in a similar way to packet communication on the Internet.

This paper reports on the world's first attempt to apply the power packet dispatching system to a drive of an electrified vehicle. We develop an experimental setup of a motor drive system with a power packet dispatching circuit. We present the experimental results of both a bench test of motor drive and an on-road test with a vehicle with the developed dispatching system installed.

II. POWER PACKET DISPATCHING SYSTEM

Fig. 1 (a) shows the schematic of a power packet. A power packet is a unit of transfer of both power and information. Power is divided into a sequence of pulses. An information tag of a voltage waveform without current is attached to each pulse power. The tag can be composed of various information such as the destination address of the power.

Fig. 1 (b) shows an example of the power packet dispatching system. A network of apparatuses called power packet routers forms the dispatching system between the sources and the loads. Similarly to the communication system, power packets can select the path to its destination from multiple candidates as a result of routing.

The routing is realized by circuit switching at each router. Fig. 1 (c) depicts the conceptual diagram of the router configuration. The router consists of switches to alter the route of power packet transfer and a buffer between them. In addition, the router has a module called an isolator at the input port to separate tag information from an incoming power packet. Fig. 1 (d) shows the operation of the tag attachment and the tag reading at a router. The tag and payload waveforms are created by circuit switching, and the separation of power and information is applied by the isolator. The two operations and the circuit realization of an isolator in this paper will be explained later in Sect. III. Besides, a more detailed and general discussion on a power packet router and an isolator module can be found in [10], [11].

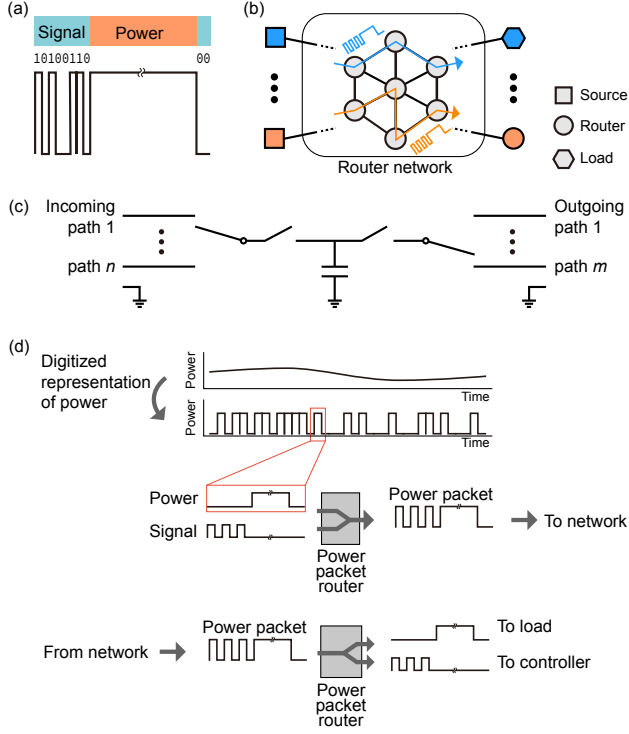


Fig. 1. Power packetization and routing: (a) Power packet, (b) Power packet dispatching through a network of power packet routers, (c) Power packet router and (d) Router's operation on power and information transfer.

III. BENCH TEST OF MOTOR DRIVE

In this section, we present the setup of the power packet dispatching system for a drive of an electric motor and the results of a bench test of the packet-based motor drive. The purpose is to confirm the feasibility of the proposed concept before the on-road test.

A. Setups

Fig. 2 (a) shows the bench test configuration. The configuration can be regarded as a subsystem of a whole dispatching system consisting in general of multiple sources and loads.

As a motor to be driven by power packets, we employ a permanent magnet assisted switched reluctance motor (PM-SRM) [12], [13]. The PM-SRM is based on a 6/4 structure with permanent magnets installed in the stator yoke. The magnets enhance the torque/power density compared to a normal SRM.

A dc generator is connected to the PM-SRM. The generator exerts a light load of a few newton meters on the motor axis.

The power packets are supplied to the PM-SRM through the power packet dispatching system. The power packet dispatching system is composed of a packet generator and a router. As mentioned above, this is the simplest configuration for the feasibility study. In a more realistic case, there should be several routers between the packet generator and the router. We omit the forwarding operation of power packets between routers, which are already confirmed in previous works [10], to focus on the routing operation for a motor drive. Below

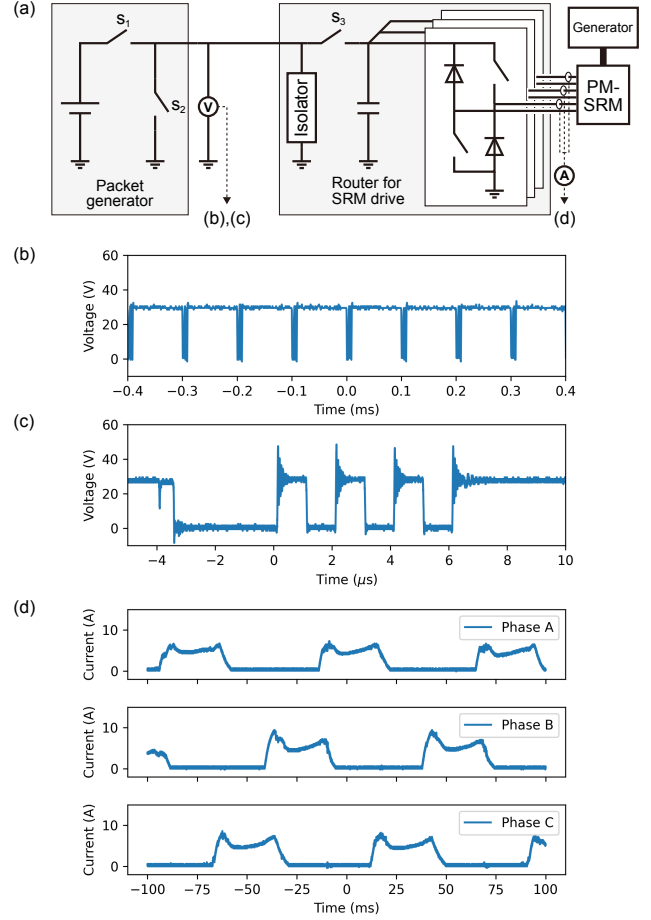


Fig. 2. Bench test of a packet-based drive of the PM-SRM: (a) Test configuration, (b) Voltage waveform measured across the output of the packet generator, (c) Magnified view of the voltage waveform around the information tag and (d) Motor's phase current waveforms.

we give a detailed description of the packet generator and the router.

The packet generator produces a sequence of power packets by circuit switching. The switches S_1 and S_2 are turned on and off in a complementary manner. The switching state $(S_1, S_2) = (\text{ON}, \text{OFF})$ corresponds to the logic "high" during an information tag transfer as well as a payload output. The state $(S_1, S_2) = (\text{OFF}, \text{ON})$ represents the logic "low" during an information tag transfer. The configuration of the header tag signal is defined as follows: "101ABC", where A,B,C $\in \{1, 0\}$ represent the presence or absence of power supply to phase A, B, C, respectively. The supply phase is determined in the packet generator's controller based on the angle position feedback so that the motor generates a positive torque. The footer signal is fixed at 00.

Then, the power packets are forwarded to the motor's phases by the router. The router can be divided into three parts: an input side, a buffer capacitor, and an output side. The input side consists of an isolator module and a switch S_3 . The switch controls the inflow of each power packet according to its tag

signal. When a power packet is recognized as addressed to the router, it turns on the switch¹. The signal is extracted by the isolator module, which is basically a combination of a voltage divider and a galvanic isolation ic. The isolator converts the envelope of a tag waveform to a logical signal of a lower voltage level and then transfers it to the controller of the router. Then the output side forwards the input power through the buffer to the motor phases according to the tag signal.

In the power packet dispatching system, the power supply is regulated by the density modulation of the power packet stream in the sense of voltage. However, the switching frequency is set much faster than the electrical time constant of the motor phases. Thus, the supply is smoothed in the sense of current waveforms.

The time length of a bit in an information tag is set at $1\mu\text{s}$. The time length of a whole power packet is set at $100\mu\text{s}$. The voltage of the power source is set at 30 V. The turn-on and -off angles are fixed throughout the experiment at 48 deg and 83 deg, respectively.

B. Results

Fig. 2 (b) shows the waveforms of the output voltage of the packet generator. It can be observed that the sequence of power packets is produced. Fig. 2 (c) shows the magnified view of the voltage waveform with a focus on the information transmission at the header tag. Following the fixed start signal of "101", the phase identifier bits indicate "010", meaning that the payload is supposed to be fed to phase B. Fig. 2 (d) shows the waveforms of the phase current of the PM-SRM. According to the tag information, the current flows in an appropriate phase. As a result, we confirmed the rotation at 190rpm with an approximately 3 N m load.

IV. ON-ROAD TEST

This section presents an application of the proposed system to a vehicle drive. We develop a golf cart powered by the PM-SRM fed by power packets. As an early stage of its feasibility study, we focus on the routing of payloads, omitting the information tag transfer/reading². A vehicle drive with their integration is currently under construction.

A. Setups

Fig. 3 shows the configuration of the cart. The circuitry of the power packet dispatching system and its controller board is installed under the seat. Next to the circuitry is the power source, which is a 90V power supply boosted from lead-acid batteries. The PM-SRM is mounted at the rear section of the cart and connected to the rear wheels via belt and gears of reduction ratio 30/13.

¹In this study, the circuit can operate without the switch; all power packets are addressed to the router because we consider only one router. However, this setup makes sense in a general case, where multiple sources, routers, and loads are installed and connected through a network of routers.

²The routing of payloads is achieved even without the tag transfer because we set an additional information path between the controllers of the packet generator and of the router.

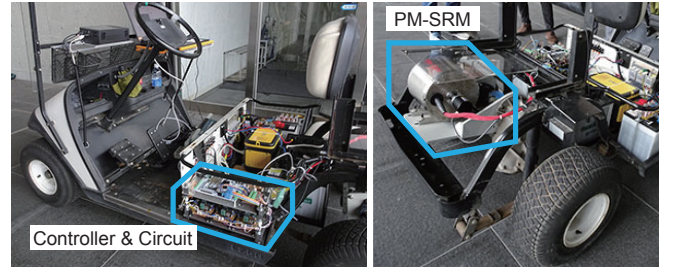


Fig. 3. Cart configuration.



Fig. 4. Photographs of the on-road test.

The power supply is controlled by the controller board in a similar way to the bench test. The accelerator pedal is connected to the relay between the source and the circuit and is used only for circuit decoupling to enable/disable the power packet feeding.

B. Results

We conducted an experiment on a 50 m straight road including a slight slope. Along the road, we made three round trips to acquire measurement data. Fig. 4 shows the consecutive photographs of the on-road test. It was confirmed that the packet-based power supply successfully drove the cart. Below we look into the measured data in detail.

Fig. 5 (a) shows the electrical input. The value is calculated by multiplying the measured voltage and current at the output of the power source. Fig. 5 (b) and 5 (c) show the output torque and rotation speed of the motor. Note that the torque and speed are measured after the gear. Thus, the rotation speed at the motor shaft is the value in the figure multiplied by 30/13; for example, at the uphill drive condition, the rotation speed of the motor shaft is ca. 1200 rpm. The mechanical output can then be calculated by multiplying them as shown in Fig. 5 (d).

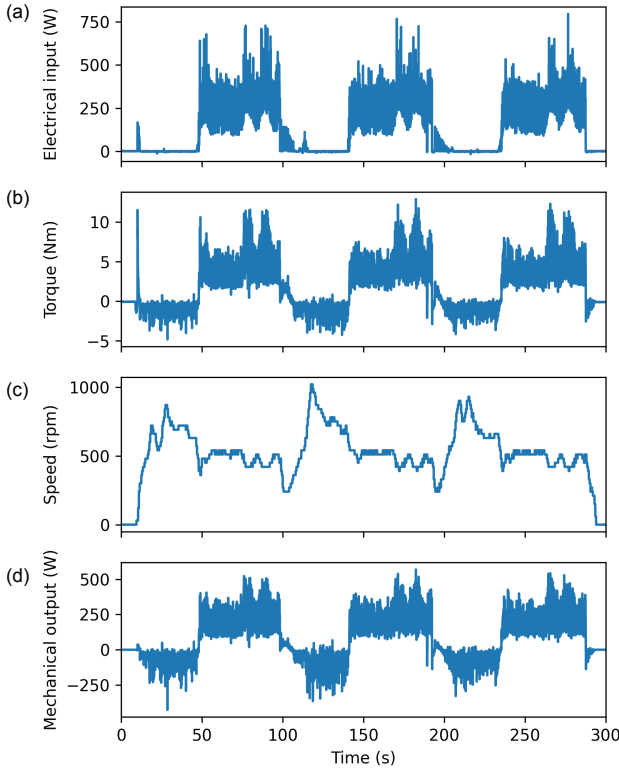


Fig. 5. Results of the road test: (a) Electrical input, (b) Output torque, (c) Rotation speed and (d) Mechanical output.

The time intervals of zero electric input and negative torque correspond to downhill traveling. At this time, the vehicle's speed is regulated by mechanical braking. While the torque is positive, power packets are supplied to the motor to achieve the constant speed drive. At this time, the power source's output is ca. 90 V, 3 A. The results indicate that the proposed packet-based drive of the PM-SRM can be employed in real-world applications.

V. CONCLUSIONS

In this paper, we demonstrated the electric cart drive with the PM-SRM fed by power packets. The two types of experimental verifications indicate the possibility of employing the power packet dispatching system in a vehicle drive system. The first experiment is the bench test which highlighted the integration of power and information transfer as power packets in a motor drive condition. The second one is the on-road test which indicated that the pulse-based power supply as a sequence of payloads can feed the motor to achieve a drive of a cart. The authors are currently working on developing a vehicle drive system with a fully integrated transfer of information and power as a power packet.

The power packetization brings Internet-like flexibility to networked management of power, e.g. the easy attachment and detachment of a subnetwork. Therefore, the proposed method is expected to be applicable not only inside each vehicle but also to interactions of elements in the V2X concept.

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