Power Packet Dispatching with Shared Power Line: Experimental Verification for Industrial Applications*

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Abstract

The power packet dispatching system is one method of electric power management with distributed power sources. The system introduces power sources and loads of different profiles and a flexible attachment/detachment of a part of them without interacting with the rest. The focus points are the physical packetization and their time-division multiplexing on the shared power line. This study verifies these concepts in industrial applications. First, experimental setups for the transfer of power packets to loads of various voltage/power requirements are developed. Then, experimental verification of the principal concepts is demonstrated with a setup assumed to be part of a robotic manipulator.

1 Introduction

With the increasing demand for eco-friendliness, the introduction of renewables and energy harvesting techniques to electric power distribution have been intensively studied. The target applications range widely, including the Internet of Things (IoT) powering, mobile robots, electric cars, aircraft, and grids [1–5]. However, a challenge remains in maintaining the balance of demand and supply under time-varying generation/consumption profiles of distributed power sources and loads. Most conventional power distribution systems adopt a common bus line for power distribution; that is, they hold the following features [6, 7].

- Power from different sources is mixed into the main bus line through power conversions so that they can be regarded virtually as a single source of large capacity.
- Each load extracts power from the bus line(s) through power conversions, assuming that the capacity of the source is large enough.

Such a scheme is based on the existence of a large and stable source; therefore, they face limitations, as discussed below.

- Using sources that have time-varying generation profiles remains only an auxiliary not to disturb the stability of the bus.
- There is no guarantee that a power system can maintain stable operation when a part of the entire system is newly connected to or disconnected from it. It might be required to add or remove sources and loads and modify the entire system, e.g., to re-design the power converters.

Principal to removing the limitations is to create a dynamic supply relationship between different pairs of a source and a load. As its possible realization, [8, 9] proposed the power packet dispatching system. In the system, each power flow is discretized as a sequence of power packets. Figure 1 (a) shows a configuration of a power packet. Power is divided into pulses, and an information tag is attached to each power pulse as a voltage signal representing a logic sequence. The tag can indicate arbitrary signals, including the origin and destination of the power. Power packets are forwarded to their destination through power routers according to the tag. Figure 1 (b) shows a part of a general power packet dispatching network between multiple sources and loads. The mixer produces power packets, and the router dispatches them to loads by circuit switching. Power packets from a corresponding source, according to the supply relationship indicated by the tag, supplies each load. The density of power packets supplied in a unit time determines the average amount of power transferred to each load. Notably, the power from different sources is distinguished in time domain and identified by physical tag attachment. They realize the dynamical supply relationship between sources and loads on the shared power line. This feature offers advantages, as discussed below.

- Sources of different (and possibly time-varying) profiles can be installed into a single dispatching system without interfering with each other.

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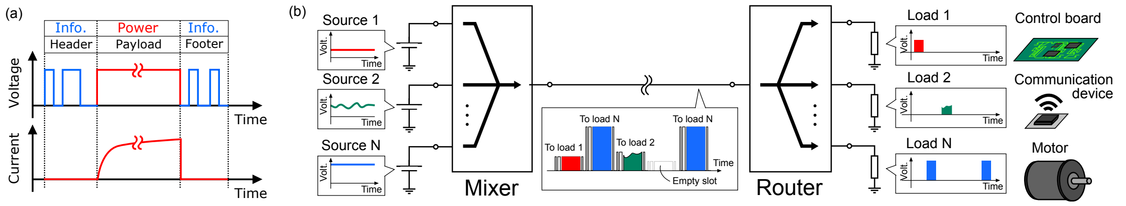

Figure 1: Power packet dispatching system. (a) Power packet (b) Example of dispatching circuit with single shared power line.

- A pair of a source and a load can be attached or detached regardless of the others, even after the system is once established.

This paper discusses the experimental implementation of the power packet dispatching system into industrial applications. Specifically, as a typical example of industrial applications, a power system included in a robotic manipulator is considered. For such applications, previous studies have highlighted a remaining issue of relatively low power transfer ratings. In industrial applications, such as robots, the power requirement of the loads ranges widely, from several watts by controller boards to some kW by motors, for example. Furthermore, the types of power demand differ depending on the loads. Some motors require a multi-phase alternate current (AC) power and controller boards direct current (DC) power. For the full exploitation of the advantages of the system, it is essential to manage the power transfer for all of these loads on the shared line. However, in previously proposed dispatching systems [8, 9], such a diversity of loads cannot be accommodated because of an immature hardware configuration. They verified the dispatching of power packets with DC loads up to 10 W, which was insufficient to drive industrial apparatuses. A simple expansion of previous hardware to the wider power level could lead to undesired operation of the dispatching system, such as misreading the tags[1].

This study contributes to both the system design and hardware development of the power packet dispatching system, allowing (1) sources and loads of different profiles to be accommodated on a single dispatching system without interfering with each other and (2) a pair of a source and load to be attached or detached even after establishing the system. These features and their concrete design principles are thoroughly discussed for the first time in this study. Then, to realize the designed system in the physical layer, the authors propose the configuration to accommodate the flow of power packets to various loads. Specifically, the following configurations are developed, as discussed below.

- Power packet generation circuit: it generates both a logic sequence and a power pulse at various voltage levels.
- Tag recognition circuit (isolator): it allows a router to extract only a signal from an information tag of a power packet with various voltage levels.
- Interface circuit: it allows the routing network to accommodate both multi-phase AC and DC loads.

The authors verify the advantages of the proposed system by conducting experiments with two sources and two loads of different ratings. The successful dispatching to loads of different types, ranging from a DC load of 10 V/4.0 W to a three-phase motor of 80 V/1.5 kW, and their flexible attachment/detachment during operation are confirmed.

Related works

The concept of power packetization and routing was first proposed in the 1990s [10]. After the proposal, several groups independently discussed power routing in packetized form ([11–14]). The authors' proposal also addresses a similar target, while it is distinguished from others because the information and power are integrated into the physical layer [9]. This aspect is critical in cyber-physical systems (CPSs), where physical systems are monitored, coordinated, controlled, and integrated with the support of information and communication technologies (ICT) [15] because the discrepancy of information and physical quantities will never be accepted in such systems.

Recently, there have been investigations on load control by power packets. Specifically, algorithms for the packet-based control were proposed and verified experimentally [16–18], and applied to a robotic system, including implementations into a robotic hand system [19] and a manipulator arm [17, 20]. However, the power ratings in previous studies were up to 10 W, which was insufficient for industrial applications. No other paper has addressed the issue so far.

2 Line-sharing Dispatching of Power Packets

This section provides an overview of the line-sharing transfer of power packets. Figure 2 (a) shows a schematic of a power packet dispatching system between two pairs of sources and loads, which is also

[1]See Section 3.2 and Fig. 6 for a detailed example of the undesired operation and its improvement by the proposed hardware.

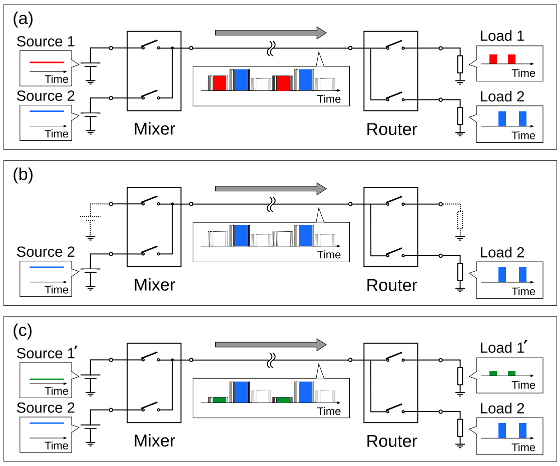

Figure 2: Line-sharing dispatching of power packets and attachment/detachment of source and load.

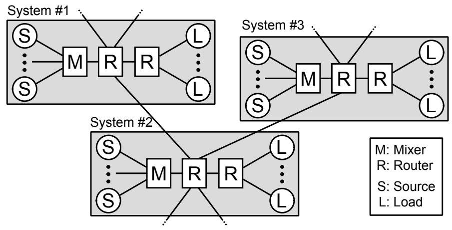

Figure 3: Network of multiple primal dispatching system.

used in the experiment later in this study. The mixer produces power packets from a DC source by circuit switching. The router allows them through or blocks them by circuit switching according to their tags. On the shared power line, power packets are transferred independently of others in their time interval. The method to manage the power flow in the time domain is called time-division multiplexing (TDM).

Here is considered replacing one supply pair, Source 1 and Load 1, with another pair. Since the transfer of each power packet is distinguished in the time domain, the pair can be detached, whereas the other (Source 2 and Load 2) keeps operating. Figure 2 (b) shows the resulting supply relationship. An additional pair can also be installed just by attaching them to the mixer and router again. Figure 2 (c) shows the configuration of the dispatching system after the attachment. The power packet transfer between the added pair is placed in the time slots that are not used in the configuration of Fig. 2 (b). In this way, the addition/removal of any subsystems can be accepted, even after the system has once been completed in its configuration.

The system can be expanded to accommodate more than two pairs until the empty time slots are used up by attaching additional input/output ports in mixers and routers parallelly. Another possible expansion is to set a network of additional routers, including loop or tree structures between the mixer and router, which is achieved easily because of the TDM transfer. Such an expansion enhances the robustness and flexibility of the system. For example, a loop structure of routers enables a power packet to choose one from multiple possible paths to reach the destination, avoiding a path with a fault or heavy traffic [9]. The possibility of the expansions also supports the generality of the experimental setup in this study. The setup of two-input and two-output is the simplest to confirm the TDM transfer with multiple sources, and is simultaneously a primal element with which any general dispatching system can be built. Therefore, the authors focus on this setup.

As mentioned above, a system can drive a maximum number of sources and loads. One way to manage more pairs of sources and loads is a parallel connection of the primal elements to form a larger dispatching network as a whole (Fig. 3). Here, power and information (as a form of a power packet) are exchanged via interface routers connecting the subsystems. Such a connection of multiple systems offers flexible power exchange; for example, surplus power in a subsystem can be delivered to another that is temporarily running short of power. Apparently, the ease of attaching/detaching of the system, which is provided by the TDM scheme, also applies to such an expansion even after the system has been built.

Lastly, a remark is given regarding the load control by power packets. In the authors' proposal, the power supply is discretized in time and quantity. A sequential supply of unit pulses of the same length satisfies the power requested from the loads. Such power digitization is essential for TDM transfer on the shared power line. Thus, the authors adopt a pulse density modulation (PDM) instead of conventional pulse width modulation (PWM). The TDM method replaces the continuous regulation of ON/OFF proportional time of continuous value with a set of power packets (i.e., a density regulation of uniform pulses). In other words, the TDM scheme does not imply that the load control by PWM is applied during ON periods, but that the sequence of ON and OFF periods of uniform length (i.e., the sequence of power packets) constitutes the regulated supply to a load. Since an OFF period for a load can be used by another load as its ON period, the power transfer rate to a specific load for an n-load system is not limited to $1/n$ of the capacity.

3 Design of Dispatching System

This section presents the experimental setup for line-sharing power packet dispatching. Figure 4 shows the schematic diagram of the dispatching circuit. The mixer produces power packets from the DC sources, and the routing circuit (RC) dispatches them to the loads according to their tags. The mixer and RC are controlled by individual controllers that generate gate signals of the switches. The controllers are implemented into field-programmable gate array (FPGA) boards, which are efficient for high-speed signal processing [21]. The timing accuracy is an essential

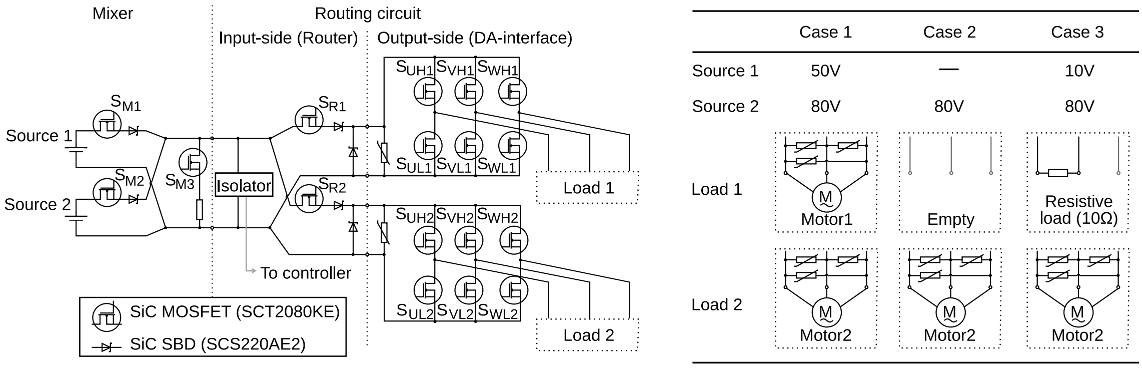

Figure 4: Circuit diagram of experimental dispatching system.

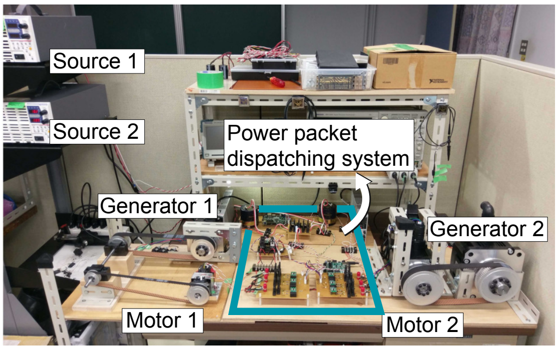

Figure 5: Photographs of experimental setups.

point in the experimental realization of TDM transfer. The detailed operation of each controller is explained in the following subsections.

3.1 Scenario

For experimental verification in Section 4, a scenario consisting of three steps is introduced.

Step 1 Supply two motors with two corresponding sources of different voltage levels.

Step 2 Detach one of the motors from the system while the other keeps operating.

Step 3 Attach another load of DC and low power ratings to the system while the motor keeps operating.

The combination of the source and load for each step is depicted on the right-hand side of Fig. 4. Step 1 confirms the achievement of TDM transfer of power packets of higher voltage levels. Steps 2 and 3 demonstrate the flexible detachment/attachment of subsystems. Step 3 also confirms that the dispatching system can include loads of different properties. Figure 5 shows an overview of the experimental setup in Step 1. Steps 2 and 3 maintain the same setup, except for the source and load.

Motor 1 is supplied by a source of 50 V, and Motor 2 by a source of 80 V. Here it is supposed that motor 1 would be installed at the wrist of the manipulator, and motor 2 at the base of the manipulator. The target operation of the motors is set as a constant speed rotation. Generators that are coupled to the motors by pulley belts consume the mechanical output of the motors. Resistors in Y-connection are attached to the output ports of the generators to consume power. The DC load for case 3 is set as a resistor of 10 Ω, and is supplied by a source of 10 V. The DC load is a controller board and requests a constant power of DC form.

3.2 Mixer

The mixer generates power packets. The proposed configuration consists of three switches, as shown in Fig. 4 as S_{M1}, S_{M2}, and S_{M3}. The mixer outputs payload power and voltage waveforms of information logic with the switches. The switches connected to the sources in series, S_{M1} and S_{M2}, are used for the output of the logic “high” and payload power. The parallel switch S_{M3} makes the voltage across the output port zero to output the logic “low.”

The addition of the switch S_{M3} is an improvement from the previously proposed configuration of the prototype mixer [8, 9] In the low state, the voltage across the mixer output must be maintained at zero. Otherwise, the router cannot recognize the tag correctly and the desired power transfer is not achieved. In the improved mixer, the output port is grounded with S_{M3} at the transition from high to low. It speeds up the transition with a quick discharge of a parasitic capacitance. For example, Fig. 6 shows the comparison of the output waveforms with the improved and prototype mixers. The transition from high to low is much faster because of the improvement. The slow transition with the prototype can cause misreading of the tag at the router because the router measures the voltage before it decreases to below the threshold. Although the bit length in the figure is used for the following experimental verification, the sharp rise and fall show that a still higher frequency can be applied, depending on its needs.

Figure 7 shows the bit assignment of a power packet. A power packet consists of 100 bits. A header includes a start signal of a power packet and a destination load address. The destination load is indicated by 2 bits: 01 for load 1 and 10 for load

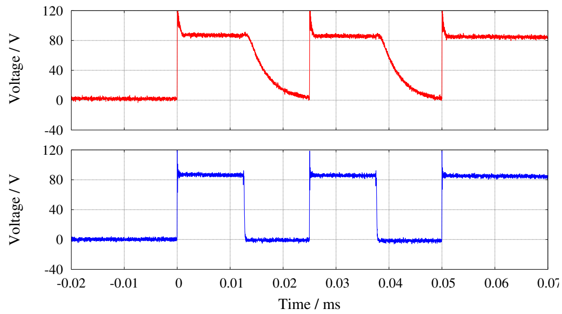

Figure 6: Voltage waveforms of information tags produced using the previously proposed mixer (top) and the developed mixer (bottom).

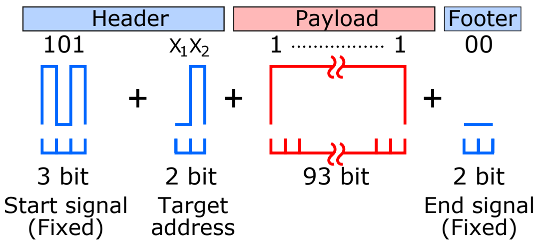

Figure 7: Bit assignment of information tag.

2, when high and low voltage are represented by 1 and 0, respectively. During the payload, the output logic is maintained on high. The footer signal shows the end of a power packet. Note that the assignment is only one example; however, different information into the tags can be added, for example. The bit length is set at 12.5 μs, corresponding to the packet length 1.25 ms. This switching frequency is chosen to be fast enough for verifying the TDM transfer in this study. The switching frequency should be higher to raise the throughput of the power packet transfer. Furthermore, the higher frequency leads to less time occupied with the information tags, contributing to better power bandwidth of the power line. The emerging wide bandgap devices, such as SiC and GaN and their driving techniques allow faster switching without remarkable losses [22–24]. The controller of the mixer is programmed to produce a sequence of power packets so that the destination load shown in the header alternates at every packet generation. This is one possible setting for confirming that the packetized power to load 1 and load 2 can share the same line in a TDM manner. Several ways exist to determine the sequence of power packets, which can be selected or even changed dynamically, depending on the purposes. Here, although the physical tag attachment is essential to realize the power packetization concept, all information exchanged in the system does not have to be included in an information tag. To avoid a mismatch of a real and calculated flow of power, information tags must include the target address of its accompanying power. However, peripheral information unrelated to the power flow control and not required to be punctual can be transferred via ways such as ZigBee and Bluetooth.

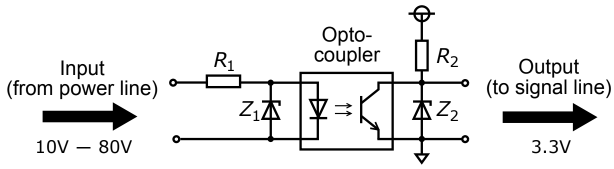

Figure 8: Circuit diagram of isolator module.

Such a combined use of multiple media increases the duration that can be used for power transfer, leading to the efficient use of a power line capacity.

3.3 Routing Circuit

The RC consists of the isolator module, the input-side circuit, and the output-side circuit. The isolator extracts only the voltage waveform of transferred power packets to pass the tag information to the controller of the RC. The input-side circuit forwards the power packets to the output-side circuit connected to the destination load. It has the same configuration as the previously proposed router; therefore, it is called a router. The output-side circuit is a newly developed module for an interface between a digital power packet dispatching system and a load that requires analog input; therefore, it is called the DA-interface. Here is given a detailed explanation of the design and operation of the isolator. In the setup of this study, the input voltage ranges from 10 V to 80 V. To protect the controller board, the isolator should output the same logic sequence at constant voltage 3.3 V as the input, regardless of the voltage level. Unfortunately, a fixed voltage divider or a direct connection of an isolator module cannot maintain the output voltage constant when the input voltage varies significantly. This study introduces the improved isolator shown in Fig. 8. The circuit solves the above issue with the configuration composed of two voltage regulators isolated with an optocoupler. The input-side consists of a voltage divider with a resistor of relatively high resistance, $R_1 = 4.7\,\mathrm{k\Omega}$, and a Zener diode, Z_1. The output-side also consists of a voltage divider with a Zener diode, $R_2 = 510\,\Omega$ and Z_2. The breakdown voltage of the Zener diodes is 3.3 V. The optocoupler isolates both sides. Note that the output logic is inverted because of the pull up type configuration of the output-side. Now, the operation of the improved isolator is confirmed. Figure 9 shows the input/output voltage of the isolator module with a 10 V input. Similarly, Fig. 10 shows the one with an 80 V input. The output logic coincides with the input for both cases. Furthermore, the voltage level of the output is maintained at 3.3 V, despite the change in the input voltage. For the router, when a header of a power packet (an information tag preceding a payload) is transferred to RC, the controller first reads the logic signal in a voltage waveform via the isolator circuit. Here, the switches are all turned off to block the current. After reading all bits of the header, the controller recognizes to which motor the payload

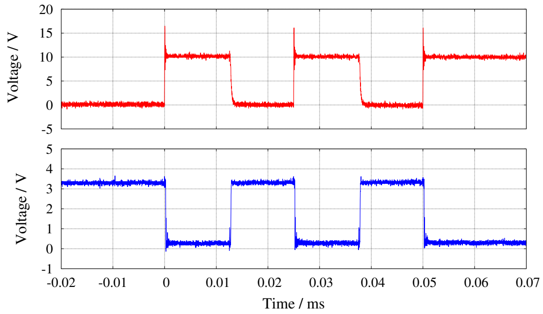

Figure 9: Input/output voltage waveforms of isolator module with 10 V input. The top curve shows the input, and the bottom the output.

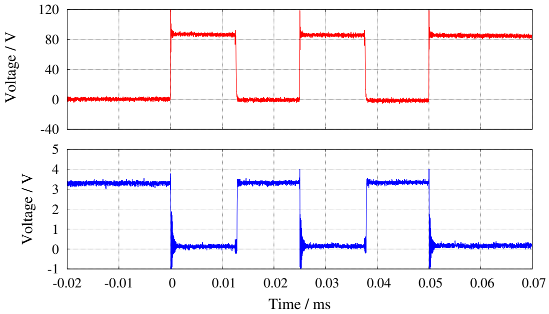

Figure 10: Input/output voltage waveforms of isolator module with 80 V input. The top curve shows the input, and the bottom the output.

should be delivered. Then, the switch corresponding with the destination motor of the payload is turned on. Lastly, when a footer signal (an information tag following a payload) is recognized, all the switches are turned off.

The DA-interface is installed to reshape the DC input of power packets into the form the load requires. The configuration can include different types of loads by changing the connection of the load to the output ports of the DA-interface. That is, the three-phase motor is connected to the three ports, whereas the DC load uses only the ports U and V. Although the circuit configuration of the DA-interface is similar to a general inverter, the difference lies in its operation. A general inverter changes the switching states on its own clock frequency, assuming a stable and uninterrupted power source as an input. However, the DA-interface receives an intermittent input of power packets. Thus, the switching states change in synchronization with the receipt of power packets. The three-phase motor's drive adopts a square-wave method in an open-loop manner [25]. That is, as shown by thick black lines in Fig. 11, the target input current waveforms of the three phases are rectangle, with a phase difference of $2\pi/3$. The supply phases p_1–p_6 in Fig. 11 are realized by circuit switching according to the rule shown in Table 1. As explained in Sect. 3.2, the destination of the power packets alternates. This means that the switches corresponding to the supply phase repeat ON/OFF according to the dotted gray lines in Fig. 11. [2] Thus, the resulting supply current to a motor is rectangles chopped in a 1/2 duty ratio, as shown by the dotted lines in Fig. 11. However, the power supply to the DC load uses only the switching state p_1; that is, switches other than S_{UH} and S_{VL} are kept off. Consequently, an alternating supply with a 1/2 duty ratio is given to the load. Note that the adoption of the square-wave drive is not a constraint for the motor driven by power packets but only one of the possible choices. The authors chose this simple scheme to focus on the verification of the line-sharing dispatching of power packets, not on the performance evaluation, such as energy efficiency and precision of control between different schemes. The important thing is how the circuit of RC, as a combination of the router and DA-interface, feeds the motors by power packets transferred through a routing network. Many other driving methods and switching rules are available. For example, the control performance should be improved by applying more sophisticated settings of the target current [26] and by adding a ripple compensation controller [27]. Such schemes can be implemented with the same physical setup maintained; it requires a modification of the software. Note that the rule should be designed so that it has an affinity with the TDM scheme (see Section 2).

Table 1: Switching rule for DA-interface of RC

Mode	S_{UH}	S_{VH}	S_{WH}	S_{UL}	S_{VL}	S_{WL}
Idling	OFF	OFF	OFF	OFF	OFF	OFF
p_1	ON	OFF	OFF	OFF	ON	OFF
p_2	ON	OFF	OFF	OFF	OFF	ON
p_3	OFF	ON	OFF	OFF	OFF	ON
p_4	OFF	ON	OFF	ON	OFF	OFF
p_5	OFF	OFF	ON	ON	OFF	OFF
p_6	OFF	OFF	ON	OFF	ON	OFF

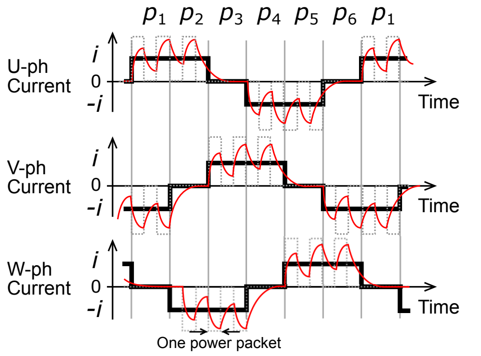

Figure 11: Target input current of square-wave drive method. The thick black lines, dotted gray lines, and thin red lines represent the target input current, ON/OFF state of the corresponding switch, and actual current, respectively.

[2]The dotted gray lines represent only the ON/OFF state; its amplitude projected to the vertical axis does not have any meaning.

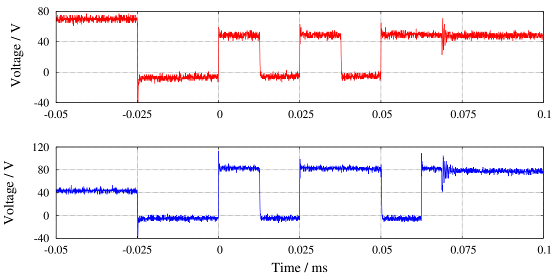

Figure 12: Voltage waveforms of information tags measured at the input port of RC. The top curve represents the waveform of a packet destined for motor 1, and the bottom for motor 2.

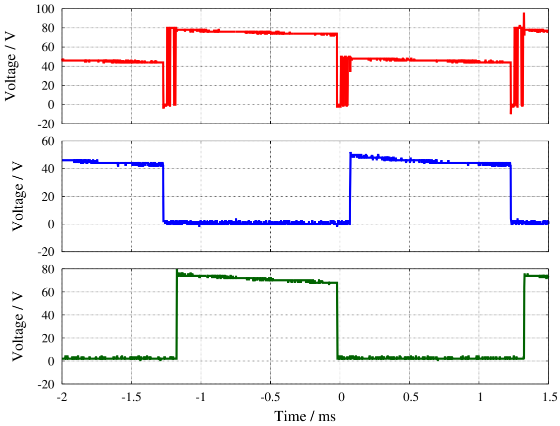

Figure 13: Voltage waveforms measured at the input and output port of the RC router. The top curve represents the voltage measured at the input port of the RC router. The middle and bottom represent the voltage measured at the output port of the RC router connected to motor 1 and motor 2, respectively.

4 Results and Discussion

Here is shown the result of Step 1. This step confirms the achievement of TDM transfer and the drive of three-phase AC motors with the DA-interface. First, the power packet generation by the mixer is confirmed. Figure 12 shows the enlarged view of voltage waveforms measured during header tags. Note that the two curves in the figure were obtained from independent measurements and their onsets do not coincide. They are depicted with an adjustment based on the rising edge of the first bit of the header. The power packet produced from source 1 (50 V) transfers the header signal 10101, indicating that the destination of the following payload power is motor 1. Similarly, the power packet produced from source 2 (80 V) transfers the header signal 10110, indicating that the destination of the following payload power is motor 2.

Based on the transferred signals, the RC router distributes the power packets to corresponding motors, confirmed from the measured input and output voltage of the router shown in Fig. 13. When power packets destined for motor 1 (motor 2) is transferred, only the switch on the motor 1 (motor 2) side is turned

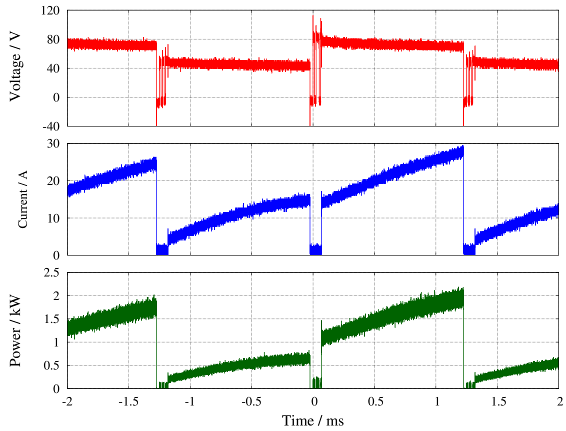

Figure 14: Output of mixer. The top, middle, and bottom curves represent the output voltage, the output current, and the output power of the mixer, respectively.

on. In this way, the power packets from different sources are transferred to the designated motors on the same power line without getting mixed. Because of the independence of each power delivery, power packets of different voltage amplitudes do not affect each other.

In Fig. 13, the information tags are lost in the bottom curve because the RC router turns on the switch after it reads the end of the header. When power packets are transferred via multiple routing circuits in a dispatching network, the tag must be reproduced at each forwarding operation. The reproduction is achieved by adopting a configuration with a buffer and additional switches [9]. In this study, only one RC is installed between the mixer and loads; therefore, the tag reproduction is unnecessary.

Next, the power packet's power delivery is observed. Figure 14 shows the voltage and current waveforms measured at the mixer output and their multiplication, i.e., the output power. The current flows only during the payloads, not during the information tags. The payloads successfully deliver the power required to drive the motors in a pulse shape: approximately 0.5 kW for motor 1 and 1.5 kW for motor 2. The results show the realization of TDM transfer in terms of power.

Lastly, the operation of the DA-interface is confirmed. Figure 15 shows the current waveforms measured at the input of motor 2. As the target supply phase changes according to the switching rule (indicated at the top of the figure), the current flows in the appropriate phases. Within each supply phase p_i, the current waveforms exhibit repeated rises and falls at every 1.25 ms because of the chopping operation of the DA-interface. A similar result is obtained for the other motor. From these results, the authors conclude that the DA-interface successfully worked as an interface between the power packet dispatching system and motors.

Now the results of Steps 2 and 3 are discussed to see the detachment and attachment of a source and

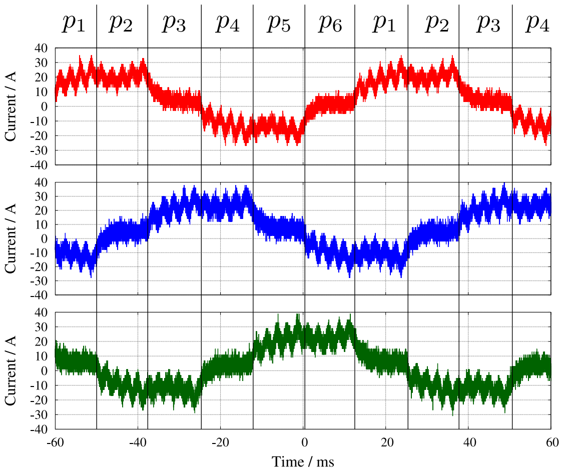

Figure 15: Input current waveforms of motor 2. The top, middle, and bottom curves represent U, V, and W current waveforms, respectively.

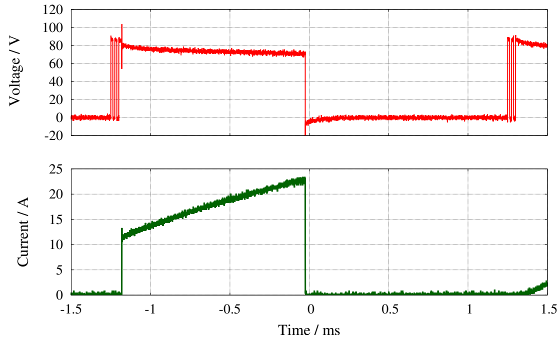

Figure 16: Power packet transfer in Step 2. Top and bottom curves represent the voltage measured at the input of the RC and the current measured at output port 2 of the RC, respectively.

load pair. Figure 16 shows the voltage and current waveforms of the transferred power packets in Step 2. The empty time slot implies that the supply between Source 1 and Load 1 is removed. However, the supply between Source 2 and Load 2 is still active and unaffected by the removal. Here the initial current at the beginning of a packet is different between the first and second packets in Fig. 16. A current leap occurs at the beginning of the first packet, whereas the current increases from zero to a certain value gradually at the beginning of the second packet because the initial current depends on the state of the inductance in the supplied phase of the motor. When a power packet is the first in a supply phase p_i, the current produced by the power packet increases from zero to a certain value gradually. Otherwise, there remains a freewheeling current (supplied by the previous power packet) at the beginning of the supply, which leads to the current leap.

Figure 17 shows the voltage and current waveforms of the transferred power packets in Step 3. Note that the vertical scales of the middle and bottom curves are changed. The power supply between Source 2 and Load 2 appears the same as in Step 2, while the

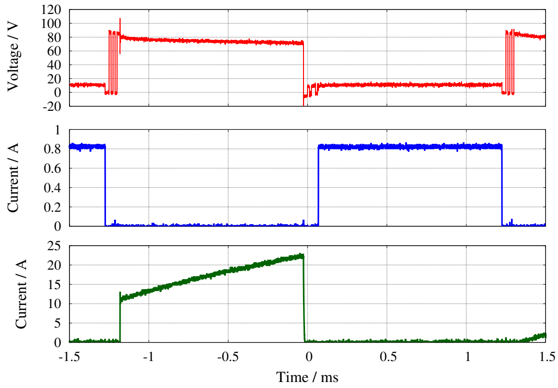

Figure 17: Power packet transfer in Step 3. Top, middle, and bottom curves represent the voltage measured at the input of the RC, the current measured at the output port 1 of the RC, and the current measured at the output port 2 of the RC, respectively.

added DC load is also supplied successfully. Although the two loads have significant differences in their power/voltage requirements, their power supply coexists on the shared power line. The results show the achievement of flexible detachment/attachment of a source and load.

5 Conclusions

In this study, the authors proposed a power packet dispatching system that accepts distributed power sources and loads of different profiles at the voltage/power levels of industrial applications. First, the design of the principal apparatuses of the dispatching circuit was proposed, namely the power packet generation circuit, the isolator circuit as a key component of the router, and the DA-interface. Then, the achievement of TDM power packet transfer on a shared power line was confirmed. Especially, the experimental verification confirmed (1) the distinguishment of power packets by the physical tag attachment and its recognition with the isolator module, (2) the coexistence of sources and loads of different types and ratings, and (3) the detachment and attachment of a supply pair while the system keeps operating. The proposed circuit configuration realizes the inclusion of various loads, ranging from a multi-phase motor of higher power ratings to a smaller DC load, which could not be accommodated by the previously proposed circuit configuration. The results show that the advantages of the power packet dispatching system (Section 1) can be held even when it is implemented in general industrial applications. The main target of the proposal in this study is to drastically improve the efficiency of power transfer between a specified pair of a source and a load; instead, the power packet dispatching can enhance the efficiency and flexibility of the whole dispatching network by creating a dynamic relationship between distributed sources and loads with the support of ICT. For such a cyber-physical interaction, the coincidence of a transfer of power and information is critical. The authors believe that the proposal will present a new direction in recently emerging applications, such as CPS and IoT, and existing industrial applications.

For such future applications, some issues must be addressed. Here is a list of some as future work.

- In the integrated transfer of information and power, noise immunity is significant. As for the information part, approaches like those in the field of communication engineering should be effective. However, in the power region, it is a novel challenge. Both hardware and software implementations, namely a noise-reducing configuration of the apparatuses and an error correction scheme for the power packet supply control should be established.

- Security issues, which are attracting much attention in the field of CPS and IoT, are inevitable in the power packet dispatching system. Many studies have addressed the security issue in communication, some of which have proposed solutions for time-division multiplexing access (similar to the proposed TDM concept), [28, 29]. However, the security issue of the combined transfer of power and information is mostly unexplored, except for a preliminary study by the authors' group [30].

References

[1] A. Abuellil, J. J. Estrada-López, A. Bommireddipalli, A. Costilla-Reyes, Z. Zeng, and E. Sánchez-Sinencio, "Multiple-Input Harvesting Power Management Unit With Enhanced Boosting Scheme for IoT Applications," *IEEE Trans. Ind. Electron.*, vol. 67, no. 5, pp. 3662–3672, May 2020.

[2] S. Seok, A. Wang, M. Y. M. Chuah, D. J. Hyun, J. Lee, D. M. Otten, J. H. Lang, and S. Kim, "Design Principles for Energy-Efficient Legged Locomotion and Implementation on the MIT Cheetah Robot," *IEEE/ASME Trans. Mechatron.*, vol. 20, no. 3, pp. 1117–1129, Jun. 2015.

[3] L. Kumar and S. Jain, "Electric propulsion system for electric vehicular technology: A review," *Renewable and Sustainable Energy Review*, vol. 29, pp. 924–940, Jan. 2014.

[4] B. Sarlioglu and C. T. Morris, "More Electric Aircraft: Review, Challenges, and Opportunities for Commercial Transport Aircraft," *IEEE Trans. Transport. Electrific.*, vol. 1, no. 1, pp. 54–64, 2015.

[5] H. Cai, J. Xiang, and W. Wei, "Decentralized Coordination Control of Multiple Photovoltaic Sources for DC Bus Voltage Regulating and Power Sharing," *IEEE Trans. Ind. Electron.*, vol. 65, no. 7, pp. 5601–5610, 2018.

[6] P. Yang, Y. Xia, M. Yu, W. Wei, and Y. Peng, "A Decentralized Coordination Control Method for Parallel Bidirectional Power Converters in a Hybrid AC-DC Microgrid," *IEEE Trans. Ind. Electron.*, vol. 65, no. 8, pp. 6217–6228, 2018.

[7] T. Kim and S. Kwak, "A Flexible Voltage Bus Converter for the 48-/12-V Dual Supply System in Electrified Vehicles," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2010–2018, 2017.

[8] T. Takuno, M. Koyama, and T. Hikihara, "Inhome Power Distribution Systems by Circuit Switching and Power Packet Dispatching," in *Proc. IEEE 1st Int. Conf. Smart Grid Commun.*, Gaithersburg, MD, USA, Oct. 2010, pp. 427–430.

[9] R. Takahashi, K. Tashiro, and T. Hikihara, "Router for Power Packet Distribution Network: Design and Experimental Verification," *IEEE Trans. Smart Grid*, vol. 6, no. 2, pp. 618–626, Mar. 2015.

[10] J. Toyoda and H. Saitoh, "Proposal of an open-electric-energy-network (OEEN) to realize cooperative operations of IOU and IPP," in *Proc. 1998 Int. Conf. Energy Manag. Power Delivery*, 1998, pp. 218–222.

[11] E. Gelenbe and O. H. Abdelrahman, "An Energy Packet Network model for mobile networks with energy harvesting," *NOLTA, IEICE*, vol. 9, no. 3, pp. 322–336, 2018.

[12] M. M. He, E. M. Reutzel, X. Jiang, R. H. Katz, S. R. Sanders, D. E. Culler, and K. Lutz, "An Architecture for Local Energy Generation, Distribution, and Sharing," in *Proc. IEEE Energy 2030 Conf.*, Atlanta, GA, USA, Nov. 2008, pp. 1–6.

[13] H. Sugiyama, "Pulsed Power Network with Scalable Operating Procedure Based on Potential Gradient," in *Proc. 2018 IEEE 61st Int. Midwest Symp. Circ. Syst. (MWSCAS)*. IEEE, Aug. 2018, pp. 552–553.

[14] J. Ma, L. Song, and Y. Li, "Optimal Power Dispatching for Local Area Packetized Power Network," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4765–4776, Sep. 2018.

[15] K.-D. Kim and P. R. Kumar, "Cyber-Physical Systems: A Perspective at the Centennial," *Proc. IEEE*, vol. 100, no. Special Centennial Issue, pp. 1287–1308, May 2012.

[16] R. Takahashi, S.-i. Azuma, and T. Hikihara, "Power Regulation with Predictive Dynamic Quantizer in Power Packet Dispatching System," *IEEE Trans. Ind. Electron.*, vol. 63, no. 12, pp. 7653–7661, Dec. 2016.

[17] S. Mochiyama, R. Takahashi, and T. Hikihara, "Close-Loop Angle Control of Stepper Motor Fed by Power Packets," *IEICE Trans. Fundam. Electron. Commun. Comp. Sci.*, vol. E100-A, no. 7, pp. 1571–1574, 2017.

[18] S. Mochiyama and T. Hikihara, "Packet-based feedback control of electrical drive and its application to trajectory tracking of manipulator," *Int. J. Circ. Theor. Appl.*, vol. 47, no. 4, pp. 612–632, Apr. 2019.

[19] T. Ando and T. Yokoyama, "Experimental Verification of Robot Hand Operation using The Power Packet Dispatching System," *IEEJ J. Ind. Appl.*, vol. 8, no. 4, pp. 638–643, Jul. 2019.

[20] S. Mochiyama, R. Takahashi, and T. Hikihara, "Trajectory control of manipulator fed by power packets," *Int. J. Circ. Theor. Appl.*, vol. 45, no. 6, pp. 832–842, Jun. 2017.

[21] L. Rovere, A. Formentini, and P. Zanchetta, "FPGA Implementation of a Novel Oversampling Deadbeat Controller for PMSM Drives," *IEEE Trans. Ind. Electron.*, vol. 66, no. 5, pp. 3731–3741, May 2019.

[22] T. Kimoto, "Material science and device physics in SiC technology for high-voltage power devices," *Jpn. J. Appl. Phys.*, vol. 54, no. 4, pp. 1–24, 2015.

[23] T. Miyazaki, H. Otake, Y. Nakakohara, M. Tsuruya, and K. Nakahara, "A Fanless Operating Trans-Linked Interleaved 5 kW Inverter Using SiC MOSFETs to Achieve 99% Power Conversion Efficiency," *IEEE Trans. Ind. Electron.*, vol. 65, no. 12, pp. 9429–9437, Dec. 2018.

[24] J. O. Gonzalez, R. Wu, S. Jahdi, and O. Alatise, "Performance and Reliability Review of 650 V and 900 V Silicon and SiC Devices: MOSFETs, Cascode JFETs and IGBTs," *IEEE Trans. Ind. Electron.*, vol. 67, no. 9, pp. 7375–7385, Sep. 2020.

[25] T. J. E. Miller, *Brushless Permanent-Magnet and Reluctance Motor Drives*. New York: Oxford University Press, 1989.

[26] M. Bertoluzzo, G. Buja, R. K. Keshri, and R. Menis, "Sinusoidal Versus Square-Wave Current Supply of PM Brushless DC Drives: A Convenience Analysis," *IEEE Trans. Ind. Electron.*, vol. 62, no. 12, pp. 7339–7349, Dec. 2015.

[27] M. Tang, A. Formentini, S. A. Odhano, and P. Zanchetta, "Torque Ripple Reduction of PMSMs Using a Novel Angle-Based Repetitive Observer," *IEEE Trans. Ind. Electron.*, vol. 67, no. 4, pp. 2689–2699, Apr. 2020.

[28] M. Tiloca, D. De Guglielmo, G. Dini, G. Anastasi, and S. K. Das, "JAMMY: A Distributed and Dynamic Solution to Selective Jamming Attack in TDMA WSNs," *IEEE Transactions on Dependable and Secure Computing*, vol. 14, no. 4, pp. 392–405, Jul. 2017.

[29] A. El Shafie, T. Q. Duong, and N. Al-Dhahir, "QoS-Aware Enhanced-Security for TDMA Transmissions from Buffered Source Nodes," *IEEE Trans. Wireless Commun.*, vol. 16, no. 2, pp. 1051–1065, Feb. 2017.

[30] Y. Zhou, R. Takahashi, N. Fujii, and T. Hikihara, "Power packet dispatching with features on safety," *Nonlinear Theory Appl., IEICE*, vol. 7, no. 2, pp. 250–265, 2016.