Power Processing for Advanced Power Distribution and Control

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SUMMARY A power packet dispatching system is proposed to realize the function of power on demand. This system distributes electrical power in quantized form, which is called power processing. This system has extensibility and flexibility. Here, we propose to use the power packet dispatching system as the next generation power distribution system in self-established and closed system such as robots, cars, and aircrafts. This paper introduces the concept and the required researches to take the power packet dispatching system in practical phase from the total viewpoints of devices, circuits, power electronics, system control, computer network, and bio-inspired power consumption.

key words: *power processing, power packet, quantized control, networking, bio-inspired system, closed system*

1. Introduction

In this paper, an advanced power distribution system and its control is proposed for advanced energy management in a self-established and closed system including various types of power sources. The closed system implies that the power network is an electrically independent system apart from the enormous power sources so that amount of available power in the system is limited. Additionally, in the closed systems such as aircrafts, cars, and robots, the available space is limited. Therefore, the space occupied by the apparatuses and wires for the energy management system should be reduced as much as possible. First, the current energy management system are summarized below. Then, we introduce a *power packet dispatching system* as one of the advanced power distribution systems satisfying the above requests, which leads to concept of *power processing*. Based on the power packet dispatching system with control, one of the effective energy management systems in closed system would be led.

Currently, various kinds of power sources are installed dispersedly in power distribution systems and the number of these dispersed sources is increasing. Those are photo-voltaic (PV) cells, fuel cells, and energy storage systems in homes and buildings, multiple batteries regulated at different ratings. The similar structure of power distribution network can be found in robots, cars and aircrafts, and so on. Most of these dispersed power sources are direct current (DC) outputs. AC power distribution is used in the major systems, however, most of loads are operated by DC. Then, the DC power distribution system is one of the candidates for aiming to decrease the steps of these AC/DC and DC/AC power conversions. However, there appear many issues as is shown in the conventional system. Even in the all DC power distribution system, the power fed by each power source should be regulated to be delivered on the common power line. Otherwise, the dedicated lines can also be prepared to link the source and load, which incur the increase of wires. From the other point of view, we need to consider the recent development of the information and communications technologies (ICT). Needless to say, it is able to process the large amount of information faster. The size of modules for communication systems also becomes much smaller, so that various kinds of the apparatuses obtain the possibility to get the communication functions. Big data of the sensors and cooperative controls among the apparatuses, which are supported by the above communication functions, has a potential to change the system management. Under the above circumstance, one of the target areas which have the potential to be improved dramatically by the ICT including the Internet of Things (IoT) or Machine to Machine (M2M) is the energy management system (EMS) to reduce the power consumption with flexible utilization of distributed power. As is mentioned above, in the current power distribution system, various kinds of dispersed power sources are installed and the number is increasing. In order to achieve the effective and safety management, ICT plays a substantial role.

Let's focus on the power distribution system targeting the closed system including various types of power sources. In the closed systems, not only the effective power management but also the effective utilization of limited space are strongly required as mentioned above. Here, we introduce the *power packet dispatching system*, and effective propose to use this system as a novel power distribution for the closed systems. The use of the power packet dispatching system in closed system have never been argued explicitly in the past or except on-going researches motivated to by our results. Please remind that the capacity of power source must be recognized as limited. At the same time, each power

Fig. 1   Schematic of one of the desired closed system.

Fig. 2   Configuration of a power packet.

source cannot be collaborated to operated the loads exceeding the source capacity. The reason why the power packet dispatching system has the potential to be appropriate for power distribution in a closed system is shown below. Additionally, in the following sections, we introduce the required researches to realize the system in practical phase from the several viewpoints. One of the possible system configurations is shown in Fig. 1. The power sources including batteries are placed dispersedly. The router has a function to forward a power packet. The packetization of electric power and time-division multiplexing (TDM) transmission scheme make it possible to share the power line among the power sources whose characteristics are different each other without being mixed. Therefore, the power packet reduces the number of wires and releases the space for another uses. While the reduction of wires, the tolerance of the power network should be high by preparing redundant routes. In the system, the dispersed power sources can be directly connected without the regulation at the common rating because TDM scheme enables to prevent interaction among multiple sources on the common power line. It implies that the power conditioner to connect the dispersed sources such as PV is not necessary. These characteristics lead the fact that the power packet dispatching system has the extensibility and flexibility; power sources and loads can be attached/removed to the system as units, with or connecting to the switching apparatus for the power packet dispatching system.

The concept of the power packet was proposed in 1990s [1], [2], as the method for many types of dispersed power sources to participate in an electrical power market without any disadvantages to existing power utilities and consumers. However, this concept was far from the reality because of the lack of the development of power devices, communication systems, and storage devices. Based on highly-developed ICT and wide-bandgap power devices such as SiC and GaN, we have developed more advanced power distribution system for the case where the capacities of installed power sources are limited [3]–[14]. This
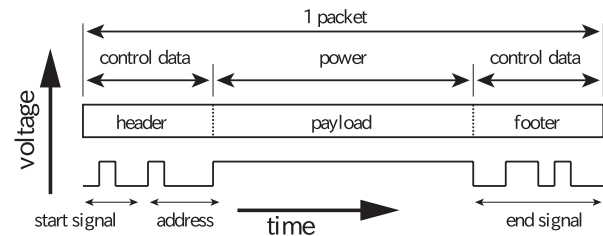
system would become more effective with the recent trend of consumed energy reduction of loads and introduction of dispersed power sources. Therefore, we newly propose to use the power packet dispatching system as a novel system for power distribution in self-established and closed systems such as robot, cars, and aircrafts. This system guides to the concept of *power processing* based on the packetization of electric power, which is the final target of the proposing project. Figure 2 shows the basic configuration of the power packet. In the system, electric power from several kinds of DC power sources is delivered as this packetized form. The information tag is attached to each power packet in the same physically layer. According to the tag information, the power packet is delivered to its destination via the routers. The power packet dispatching system is designed to integrate the information and power networks at the physical layer. TDM transmission scheme enables the various kinds of power packets to share the common power lines without restricting the accumulation of power but watching the rating of single power packet at each time duration. One of the aims for the power packet dispatching system is to realize a power on demand which implies the each load demands the power as much as necessary from appropriated power source. In order to transmit an information from load to source, low-power and small module for communication would be necessary, whose development is progressing in the context of IoT and M2M.

In the following sections, we show the concepts and researches based on the power packet dispatching system in the effective closed system. In Sect. 2, recently-developed prototypes of the mixer and router to construct the power packet dispatching system are shown with the experimental verification. In Sect. 3, the control of multiple loads in power packet dispatching system is discussed. Section 4 shows the concept of protocol design for the power packet dispatching network. In Sect. 5, the concept of robot driven by the power packet dispatching system is proposed and discussed. Finally, the potential for expansion of the power packet dispatching system is discussed in Sect. 6.

2. Prototypes of Power Packet Dispatching System

The power packet consists of header, payload, and footer. Figure 2 shows the basic configuration of the power packet. The payload carries the power, which implies electric current exists in the duration of payload. As an information tag, the header and footer are attached to the payload as
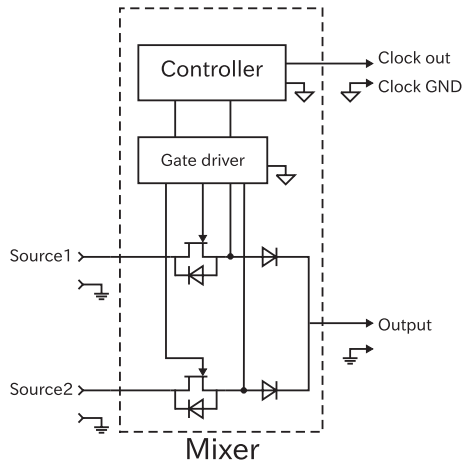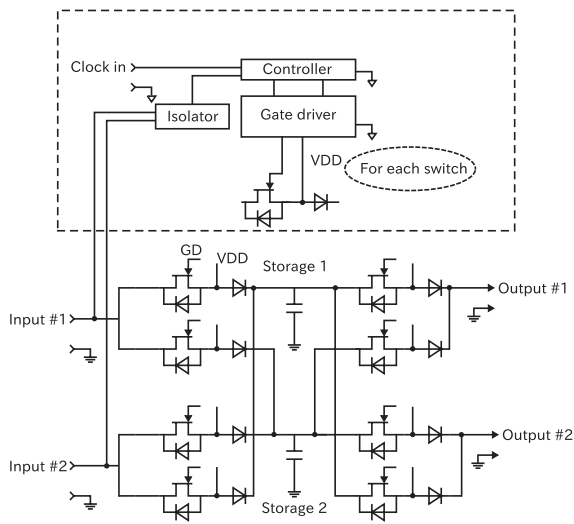
Fig. 3　Configuration of mixer.

Fig. 4　Configuration of router.

the voltage waveform physically. The header includes the start signal, the addresses of source and load. The footer includes the mark to notify the end of packet. The number of bits and its information in tag can be changed arbitrary. In order to construct the system, the apparatuses, i.e. mixer and router, are proposed and these prototypes were verified [6]–[8]. With the proposition of these apparatuses, the feasibility of the power packet and its dispatching system was investigated and experimentally verified. The mixer converts DC power of connected sources to power packets. The router forwards the received power packet to the objective destination according to its tag information. Additionally, the storages are installed in the router, so that the router has the store-and-forward function as the router for the packet communication has. The prototype configurations of the mixer and router are depicted in Figs. 3 and 4, respectively. In the prototypes, SiC junction field-effect transistors (JFETs) (1200 V, 27 A) are adopted as the switching power devices. To prevent inverse current, a Fast Recovery Diode is connected in series with each switching
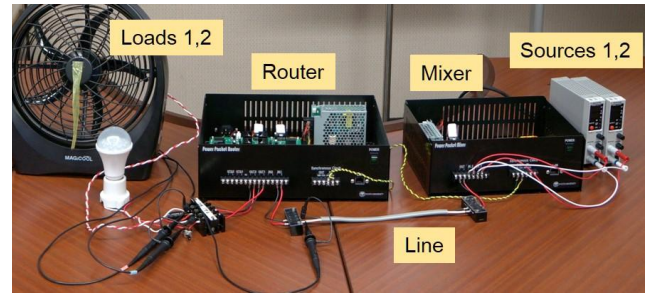

Fig. 5　Experimental setup of the power packet dispatching system.

power device. The mixer in Fig. 3 has two input and one output port, and the router in Fig. 4 has two input port and two output port. The power source of power packet is connected to each input port of the mixer. The voltage waveform of power packet is formed by ON/OFF operation of the switch, so that the wide band-gap power devices with high-frequency and low-loss switching are essential. In the prototype mixer, the generated power packets are transmitted from common output port. While one switch in series with one power source is ON state, the others are OFF. It indicates that the TDM transmission scheme is adopted in the system. These switches are controlled to generate power packets to satisfy the demand from loads. On the other hand, the router has a function of forwarding the received power packet to the objective destination. The controller in the router reads the tag information attached to the received power packet via isolator. Once, the received power packet is stored in the selected storage. Then, according to the tag information, the power packet, which is generated from the storage and whose information tag is renewed, is dispatched to the other router. The storages in the router are separately used in accordance to the power source or its voltage to avoid the mixing of power. Therefore, the number of storages would be more than the number of sources connected to the system. The appropriate number of storages would be found. The power loss in the prototype system was evaluated [11]. In the case that 12 V and 100 mA power packet passed thought a router, about 0.1 W power was lost. Around 90% of power loss is on the diodes. These power loss would be reduced by adopting more effective power devices such as SiC diode. Figure 5 shows the photo of experimental setup to evaluate the feasibility of the power packet dispatching system. Figure 6 shows an example of the measured power packet waveform. In the prototype system, a clock signal is transmitted through a signal cable for keeping clock synchronization among the mixers and routers. Currently, it was also proposed and experimentally verified that the clock synchronization can be achieved by the preamble bit added before header of power packet [9], [10]. By using these prototypes of mixers and routers, the feasibility of networking and extensibility can be evaluated. Actually, in [11], the small networked system was constructed and packet dispatching on its system was confirmed. In addition, the power supplies by power packet to various kinds
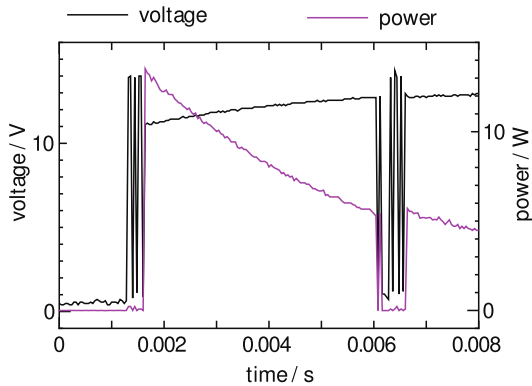
Fig. 6   Measured waveform of the power packet.

Fig. 7   Power packet dispatching system for multiple control systems.

of loads such as LED bulbs and batteries were verified. In particular, stepper motor drive by power packet and its system were also proposed and verified [12], [13]. The wide band gap semiconductor is a key to develop the power distribution system with power packet. The conventional Si based system has no hope. The concept cannot be accepted without developing the hardwares which perform power distributions in the physical layer.

3.   Packet-Based Control

One of the key techniques for power packet dispatching systems is the *packet-based control*, i.e., the control with intermittent power supply.

Let us consider the power packet dispatching system for multiple control systems as shown in Fig. 7. In this system, a router procures packets from a power packet network and provides them to N control systems. Then a single control system can receive a packet (i.e., power) at each time instant, and the other $N - 1$ control systems are operated without power for a while. As a result, the power supply for the control systems is intermittent, and the packet-based control plays an important role in each control system.

In realizing the packet-based control, two estimation techniques, which will be implemented in each control system, should be developed. One is the estimation of the time to the critical state of the corresponding control system. The time is equivalent to the necessity of a packet, and it can be estimated by utilizing a mathematical model of the control system. The other is the estimation of the necessary quantity of power, which corresponds to the power which has to be contained in a packet. For the estimation, a series of results of the *quantized control* (e.g., [15], [16]) would be useful.

The packet-based control is a feasible technique for power packet dispatching systems. Figure 8 shows our experimental setup to evaluate the feasibility of the packet-based control in a power packet dispatching system. This setup is composed of four control systems with a seesaw and ball, and aims at regulating the position of each ball at the center of the seesaw. We have already succeeded in an experiment, which suggests the possibility of the packet-based control.
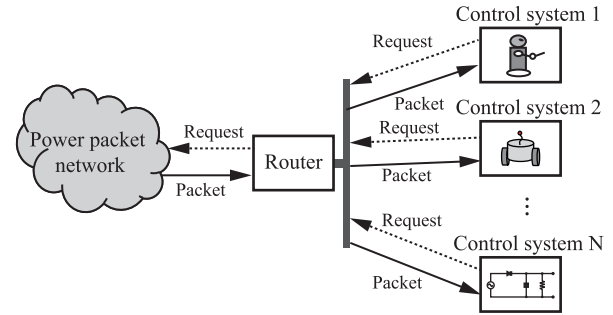

Fig. 8   Experimental setup for feasibility study of packet-based control [17].

4.   Optimal Protocol Design on Power Packet Dispatching Network

For controlling systems using the power packets, development of a new protocol for the power packet dispatching networks is necessary. The packet delivery delay should be sufficiently small to enable controlling systems correctly. A required amount of the power has to be delivered to the target system load in a required time. Different from the communication networks, the bitrate is not fast as the order of Gbps. Therefore, the number of information bits in the packet headers has to be small for shortening the delay. On the other hand, similar to the Internet, extensibility of the system has to be supported. Information tags have to be included in the packet if it is necessary. Obviously, the collision and congestion of power packets which possess the electricity should be also taken into account for protocol design. The most of the requirements on the power packet dispatching networks for the system control are different from the conventional communication networks and cannot be satisfied by the current communication protocols.

The current TCP/IP protocol was designed based on the OSI reference model having 7 layers. The data packets generated at the application layer of the sender side is transmitted with attaching various headers at the lower layers. When a data packet is transmitted over the Ethernet network using TCP protocol, the total length of the packet header becomes at least 432 bits, which are 160 bits for the TCP layer, 160 bits for the IP layer and 112 bits for the Ethernet head-

ers. Such a packet header is too long for the power packet dispatching networks, because its bitrate cannot be as fast as communication networks and the packet delay should be small for controlling systems.

In order to deliver the power packets to the right destination node, packet routing is necessary, while the most of other roles of the current communication protocols can be omitted in the power packet networks. In the current Internet, two addresses are used, the Ethernet address corresponding to the hardware and the IP address corresponding to the position in the network. Such a separation of roles to multiple layers makes design of the network easy. However, the power packet dispatching networks for system control have to be more efficient from the viewpoint of the bandwidth (bitrate) of the networks.

We develop new designing methods for the power packet format and the power packet network architecture. For the optimal design of the power packet format as in Fig. 2, we formulate an optimization problem to satisfy the following conditions, the necessary amount of the power have to be delivered for each load, the packet delivery delay have to be shorter than that required by the target control system, and the bitrate of the power packet routing hardware may be limited in kbps to Mbps. In some control systems, information tags have to be also included in the packets. We derive the optimum packet format based on such conditions described above. Also the network architecture as shown in Fig. 1 shall be optimized to satisfy the conditions of the control system's requirements. When the number of the loads becomes huge, the number of the power sources may be needed to increase and multiple links and routes may be prepared for the loads. For shortening the packet delivery delay, batteries may be added at the closer point to the target load in the networks and will be charged from the power sources in an optimal way. While the number of the power line links should be small for making a total system small and light, the tolerance of the power network should be high by preparing redundant routes. In our previous research, we have designed and implemented centralized and decentralized optimization algorithms for network resource allocation [18]. Such algorithms will be extended for optimizing the packet format and the network architecture of the power packet dispatching networks. We develop a new protocol for the power packet dispatching networks based on the optimized packet and network structure.

5. Bio-Inspired Power Delivery and Consumption Based on Power Packet Dispatching System

In this section, we discuss a concept of energy management system which follows power delivery and consumption in biological systems. First of all, we mention a difference between the power packet and that in the Internet. In the Internet, information is transmitted by means of network packets and those packets are disappeared after the information is processed. On the other hand, the power packet transfers electricity simultaneously with information about

its delivery targets. By using the property of carrying both information and power, we consider extra power storages such as batteries or capacitors attached to distributed loads as shown in Fig. 1, where transmitted power can be stored and used when it is necessary. Those distributed power storages imply that power packet is not necessarily disappeared after transmitting information. To operate such power storages, a memory-like mechanism by which the power packet is written into and read out from those storages is required. It should be noticed that the conventional power conditioner has the potential to work as on-demand power storage operation which is similar to the proposed system. However, the switching function in the power network is required to deliver the power from the requested power source to the target load without being mixed with the one from the undesired source. Normally, the power conditioner does not have such a switching function. On the other hand, in the power packet dispatching system, the discrete power packets are exchanged among nodes in a power network by switching the connections between sources and loads. To achieve such purpose, we consider bio-inspired algorithm for constructing those switching networks. One of possible switching algorithm is proposed in Ref. [19].

As a possible mechanism for achieving that memory-like power storage, we consider a scheme of glucose metabolism in skeletal muscle [20]. In the metabolic system, glucose is processed for generating energy to move muscle and is represented by a discrete unit, i.e. the molecule $C_6H_{12}O_6$. Moreover, when the glucose is conveyed to a skeletal muscle, it is converted to glycogen, which is a polymer molecule composed of glucose, and stored at the muscle as shown in Fig. 9(a). Due to such discrete property, there is an analogy between glucose metabolism and the power packet dispatching system. That is, the power packet is a discrete form of voltage as well as glucose is a molecule for ATP, i.e. energy for muscle motion. Therefore, we consider a model of glucose metabolism in skeletal muscle and apply it to the power packet dispatching system. As described in the Fig. 9(a), the glucose corresponds to the power packet. Then, the liver corresponds to a power source which has the function of the router and the mixer. The liver generates glucoses (power packets) which are transmitted via blood to muscles. Here, muscles correspond to the loads with the storage which also have the function of the router and the mixer to transmit the power to other loads. The advantage of using the mechanism of glucose metabolism is that the amount of power storage can be adapted according to the activity, which is explained below.

Furthermore, we add a function by which maximum amount of power storage is adapted according to the usage of the load. By introducing this function, it is expected that efficiency of power consumption is better than without this function, since it can reduce a consumption of standby power at loads. The function follows the plasticity of skeletal muscle, namely muscle expands when its activity is high and shrinks when it is low. See Fig. 9(a).

As another aspect of relation between metabolism and
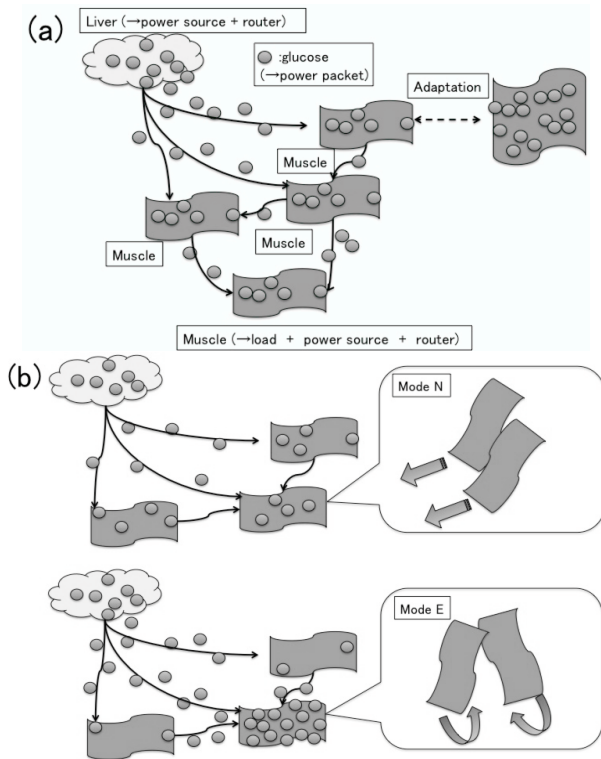
Fig. 9 Schematic illustration of glucose metabolism and modes of muscle motion.

muscle motion, we consider the moving modes of the muscle. For example, there are three modes of ponies walking, that is, walk, trot, and gallop. It is observed that there exists the optimal speed for each walking mode regarding energy consumption [21]. The change of walking modes can be interpreted as animals select optimal parameter for moving their muscle in order to save energy consumption. This concept can be applied to artificial systems in view of power supply for emergency. That is, by selecting optimal paths and sources for power delivery regarding normal and emergency modes (e.g., modes N and E in Fig. 9(b)), energy management system can supply extra energy for emergency use and save that extra amount of energy in a normal situation. For example, glucoses in a muscle are consumed at the beginning of high-intensity exercise of the muscle. After initial glucoses in the muscle is used up and the intensity of the exercise becomes low, further glucoses are supplied to the muscle from other muscle or blood.

6. Remarks

In this position paper, the concept of the power packet dispatching system and its research and development are introduced. The power packet dispatching system is designed as the integration technologies of the information and power networks at the physical layer. Therefore, especially in practical phase, the system design requires interdisciplinary collaboration. In this position paper, we introduced the researches of the power packet dispatching system from the

viewpoints of devices, circuits, power electronics, system control, computer network, and bio-inspired power consumption.

The power packet dispatching system has been developed as the effective energy management system for the case where the capacities of installed power sources and the space are limited. In the system, the common power lines can be shared by various types of power sources without restricting the accumulation of power, so that the wires can be reduced and the space is released for another use. In addition, the system has the extensibility and flexibility, which implies that power sources and loads can be attached/removed to the system as units.

This power packet dispatching system has a potential to cause the digitalization in power distribution, as was appeared in communication field. Such a digitalization of energy also leads the dramatic change of any electric and electrical equipments, which also implies the change of lifestyle. The digital or quantized power distribution, which is called *power processing*, let us open to the new era of the system design of practical system with power network.

Acknowledgment

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