

LETTER

Up-Stream Dispatching of Power by Density of Power Packet

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SUMMARY Power packet is a unit of electric power transferred by a pulse with an information tag. This letter discusses up-stream dispatching of required power at loads to sources through density modulation of power packet. Here, power is adjusted at a proposed router which dispatches power packets according to the tags. It is analyzed by averaging method and numerically verified.

key words: power packet, up-stream dispatching, router, power density

1. Introduction

In sharing energy between sources and loads in an electrical energy network, there exist up-stream dispatching of required power to sources and down-stream dispatching of supplied power to loads [1]. With information and communication technologies, the network can possibly adjust the best matching of supplies and demands in on-demand manners [2], [3]. However, with physically coupled sources and loads, it is apparently difficult to realize the desired supplies and demands simultaneously in the network. Thus, the key is to directly and physically process the power in the network. To this end, we introduce power packetization.

Power packet is defined as a unit of electric power transferred by a pulse with an information tag. The concept of power packet was proposed from the viewpoint of suppliers by Toyoda and Saitoh in 1990s [4]. “Energy packet networks” were also proposed to provide energy on demand to Cloud Computing servers [5]. Recently, wide-bandgap power semiconductor devices, which have the potential to realize higher frequency switching and higher power capacity than Si power devices, have been developed [6], [7]. The authors’ group has developed a power packet dispatching system in physical layer applying these high-performance power semiconductor devices [8]–[11]. In the system, power packets are directly and physically tagged as their voltage waveforms. The system consists of network lines and routers which forward power packets according to the tags. Energy storage is integrated into the router to adjust the forwarding of power packets. It is also confirmed that the router realizes power transfer using time-division multiplexing (TDM) without keeping synchronization of clocks for generating packets between routers*. Considering the pair of information tags and power pulses as a symbol, power packet transmission is found as a problem

of simultaneous representation of message and energy using symbol sequences in a similar way to the Shannon’s information theory [12].

The up-stream and down-stream dispatching of power can be dynamically realized by routing power based on the tags of packets. Here is handled the power as the density of power packet [13]. Up to now, the method for generating power packets is proposed to realize desired dynamical behavior of the objective loads with dynamic quantizer for discrete-valued signal [14], [15]. The aim of down-stream dispatching is to transfer limited amount of supplied power to multiple loads. On the other hand, the aim of up-stream dispatching is to transfer required power from multiple sources in the desired amount of power.

In this letter, we focus on the up-stream dispatching of required power at loads to sources through density modulation of power packet in transmission. It is discussed at a router, i.e. a unit element of the network which dispatches power packets spatially and temporally based on information tags. Here, we show the relationship between transferred power into the router and density of packets in transmission. The relationship is analyzed by averaging method [16] and numerically simulated taking dynamics of the storage integrated into the router into account.

2. Up-stream Dispatching of Power at Router

2.1 Power Packetization and Function of Router

Here, we explain the configuration of power packet and the function of router based on our developed system [9]. A power packet consists of header, payload, and footer. The payload brings power, while the header and the footer carry the information of the packet’s tag. The information tag identifies varieties of power due to different sources, loads, voltages, and so on.

A router is designed for multiple inputs, outputs, and storages implemented with capacitors. The schematic configuration of the router is shown in Fig. 1. Varieties of power, which are identified at lines by tags’ information, are identified in the router by multiple storages. Thus, varieties of power can be separately and individually managed in a single network.

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*The packet itself contains the preamble for recognizing the sent information and fixing the clock of receiving router [10], [11].

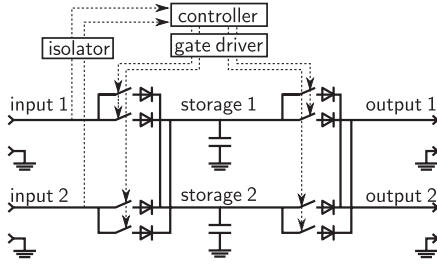


Fig. 1 Schematic configuration of the router with two inputs, two outputs, and two storages [9].

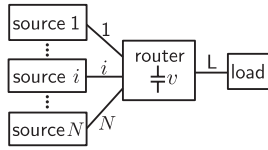


Fig. 2 Schematic diagram of system to investigate up-stream dispatching of power at router.

2.2 Problem Setting

With handling power as continuous flow by averaging [13], this letter focuses on up-stream dispatching of power packets stored at a same storage in each router. Power packets are physically coupled if they are stored at a same storage. Except it, there is no coupling. In the up-stream dispatching, a router is supplied with required power of loads from multiple sources and through multiple passes.

The up-stream dispatching is investigated at the setting in Fig. 2. In the system, power packets are asynchronously transferred to the same storage through multiple inputs. The input ports are indexed by a finite set $I = \{1, 2, \dots, N\}$ and the output port is indexed by "L". The power packets transferred at the port $i \in I$ to the storage is called packet i and power packets transferred at the port L from the storage is called packet L.

Considering a finite duration, u_i denotes the average power transferred by packet i for $i \in I \cup \{L\}$. σ_i denotes density of packet i in transmission, i.e. the proportion of the payload of the packet i . For a time series x , $\langle x \rangle$ denotes the average of x . For packet i with non-empty payload, $\langle x \rangle_i$ denotes the average of x over the payload of the packet i . Considering a stationary state, the problem of up-stream dispatching is treated by the proportion of each transferred power $\{u_i\}_{i \in I}$ in the total supplied power $\sum_{i \in I} u_i$.

Finally, the operation of the system is explained as follows. For $i \in I$, the source of the packet i is treated as a Thévenin equivalent circuit with open-circuit voltage $e_i \geq 0$ and resistance r_i . The support of e_i corresponds to the payload of packet i . By definition, $\langle e_i \rangle = \sigma_i \langle e_i \rangle_i$. As for the router, the storage capacitance is set as C and the voltage across the storage is denoted by v . A diode is placed at each switch to protect the reverse current as in Fig. 1, so that the reverse current is prevented at the time of $e_i < v$

for each $i \in I$. The router regenerates the packet L with the voltage equal to v during the payload. The load is treated as resistance R with PFC circuit, which requires energy $u_R = \sigma_L E_0^2 / R$, where E_0 is a base value of voltage[†].

3. Analysis by Averaging Method

Here, we analyze the relationship between transferred power into the router and the density of packets in transmission. In the analysis, we assume small ripple fluctuation of the voltage v . According to the averaging method [16], we approximate $v \approx \langle v \rangle$.

At first, we consider a small ripple fluctuation of e_i for $i \in I$ and a small difference between $\{e_i\}_{i \in I}$ enough to have $e_i > v$ for all $i \in I$. The packet i transfers power approximated by

$$u_i \approx \sigma_i \langle v \rangle \frac{\langle e_i \rangle_i - \langle v \rangle}{r_i} \quad (1)$$

In addition, the following equation is led by averaging the constraint equation of the Kirchhoff's current law at the router's storage in a stationary state.

$$\sum_{i \in I} \sigma_i \frac{\langle e_i \rangle_i - \langle v \rangle}{r_i} \approx \sigma_L \frac{\langle v \rangle}{R} \quad (2)$$

or

$$\langle v \rangle \approx \frac{\sum_{i \in I} \frac{\sigma_i}{r_i} \langle e_i \rangle_i}{\sum_{i \in I} \frac{\sigma_i}{r_i} + \frac{\sigma_L}{R}} \quad (3)$$

Using Eqs. (1) and (3), we can derive the proportion of the transferred power by packet j for each $j \in I$:

$$\frac{u_j}{\sum_{i \in I} u_i} \approx \frac{\frac{\sigma_j}{r_j} \langle e_j \rangle_j + \sum_{i \in I} \frac{R}{\sigma_L} \frac{\sigma_i}{r_i} (\langle e_j \rangle_j - \langle e_i \rangle_i)}{\sum_{i \in I} \frac{\sigma_i}{r_i} \langle e_i \rangle_i} \quad (4)$$

If differences at source sides are negligible, the densities of power packets give the proportion of each transferred power. In other words, if $\langle e_i \rangle_i = \langle e_j \rangle_j$ and $r_i = r_j$ for all $i, j \in I$, the proportion can be written as

$$\frac{u_j}{\sum_{i \in I} u_i} \approx \frac{\sigma_j}{\sum_{i \in I} \sigma_i} \quad (5)$$

This relationship shows the possibility of dynamical adjustment of the up-stream dispatching of power at routers in a network through density modulation of power packet.

Finally, we briefly discuss the case $e_i < v$ for some $i \in I$. During $e_i < v$, no power is transferred by packet i , because the diode at link i prevents reverse instantaneous power [11]. Therefore, the effect of the diodes should be taken into account by using power density at port $i^{\dagger\dagger}$ instead

[†]In the whole network, the base value of voltage may be different depending on the varieties of power identified by tags and storages [9].

^{††}Power density at port i is the proportion of support of instantaneous power at port i , which is included in the payload of packet i . The power density at link i takes a value between 0 to σ_i .

of σ_i which is the density of packet i in transmission.

4. Numerical Verification

The analytical results in Sect. 3 are obtained with the small ripple fluctuation of the voltage v across the capacitor. In this section, the relationship between transferred powers and packet densities is numerically verified by simulating the dynamics of the voltage v . For simplicity, we consider the case in which the number of inputs are two, i.e. $I = \{1, 2\}$. As an example, the basis of the system is set by $E_0 = 12$ V and $u_R = 1$ W. Each packet is periodically transmitted with the period from 0.5 ms to 5 ms[†]. The payload of packet 1 and packet 2 has rectangular waveform of voltage, i.e. $e_i = \langle e_i \rangle_i$ on the payload for $i \in \{1, 2\}$. We set $C = 1000 \mu\text{F}$ and $r_1 = r_2 = 1 \Omega$. The transferred powers u_1 and u_2 are defined in a duration of 100 ms.

In the following, the transferred powers $\{u_i\}_{i \in I}$ are calculated in various settings of densities $\{\sigma_i\}_{i \in I}$ in the both cases of $\langle e_1 \rangle_1 = \langle e_2 \rangle_2$ and $\langle e_1 \rangle_1 \neq \langle e_2 \rangle_2$. The period and the phase of each packet are uniformly distributed. The density σ_L is uniformly distributed from 0 to 1, and then the resistance of the load is decided as $R = \sigma_L \cdot E_0^2 / u_R = \sigma_L \cdot 144 \Omega$. The switches and diodes in the router are ideal in the simulation.

4.1 In Case of $\langle e_1 \rangle_1 = \langle e_2 \rangle_2$

At first, we discuss the case of $\langle e_1 \rangle_1 = \langle e_2 \rangle_2 = E_0$. The relationship between transferred powers and packet densities is examined in the simulation by uniformly distributing σ_1 and σ_2 from 0 to 1. The results of 10,000 trials are plotted in Figs. 3 and 4. Figure 3 shows that, almost regardless of the dynamics, the densities of power packets give the proportion of each transferred power as in Eq. (5).

Figure 4 shows that the total required power is satisfied with the sufficiently large sum of densities, but is not satisfied with the small sum of densities. Here, using Eq. (3), the total transferred power can be approximated by averaging method as

$$u_1 + u_2 \approx \frac{\langle v \rangle^2}{R} = \left(\frac{\sigma_1 + \sigma_2}{\sigma_1 + \sigma_2 + 0.0069} \right)^2 \text{ W} \quad (6)$$

This relationship, shown in Fig. 4 as a solid line, approximates the simulated results well. Thus, the sum of densities should be set sufficiently large in order to keep the voltage across the capacitor close to E_0 and supply sufficient power.

4.2 In Case of $\langle e_1 \rangle_1 \neq \langle e_2 \rangle_2$

Next, we discuss the case of $\langle e_1 \rangle_1 \neq \langle e_2 \rangle_2$. As an example, we set $\langle e_1 \rangle_1 = 12.5$ V and $\langle e_2 \rangle_2 = 12$ V. The relationship

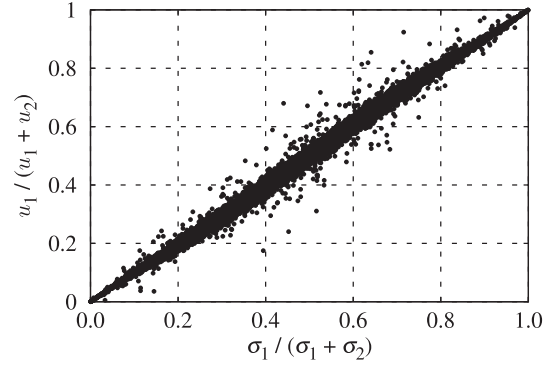


Fig. 3 Relationship between proportion of transferred power by packet 1 and packet densities at $\langle e_1 \rangle_1 = \langle e_2 \rangle_2 = E_0$.

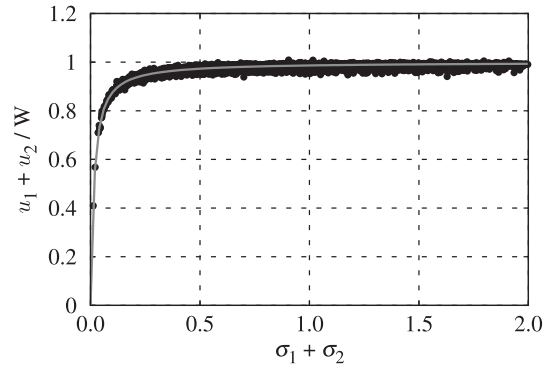


Fig. 4 Relationship between total amount of transferred power and packet densities at $\langle e_1 \rangle_1 = \langle e_2 \rangle_2 = E_0$. The solid line shows the relationship of Eq. (6).

between transferred powers and packet densities is numerically examined again by uniformly distributing σ_1 and σ_2 from 0 to 1. The simulation was repeated 10,000 times and the results were drawn in Figs. 5 and 6. In Fig. 6, to ignore the effect of the voltage drop, only the results with the sufficiently large sum of densities are plotted.

Figure 5 shows no power is transferred by packet 2 if σ_1 is not small. This means the power density at link 2 becomes 0 for all possible values of σ_2 if packet 1 is frequently transmitted. Fig. 5, however, also shows the proportion of transferred power by packet 2 ranges from 0 to 1 if σ_1 is sufficiently small. In addition, Fig. 6 shows, if the sum of densities is sufficiently large, i.e. $\sigma_1 + \sigma_2 > 0.3$ in this case, the required power is satisfied^{††}. These results imply, even if the difference between source voltages is not small, we can adjust the proportion of input power by setting small the densities of packets with high voltage in transmission.

Using 10 different seeds for the random number generator, similar simulation results are obtained with Figs. 3, 4, 5, and 6, which ensure the consistency of the results.

[†]In this simulation, the time series of packet L is assumed to be independent from the time series of inputted packets. In our developed router, the packet L can be regenerated based on the time series of inputted packets by router's algorithms [9].

^{††}The transferred power slightly decreases when σ_1 is small. The result implies that the supplied voltage varies from $\langle e_1 \rangle_1$ to $\langle e_2 \rangle_2$.

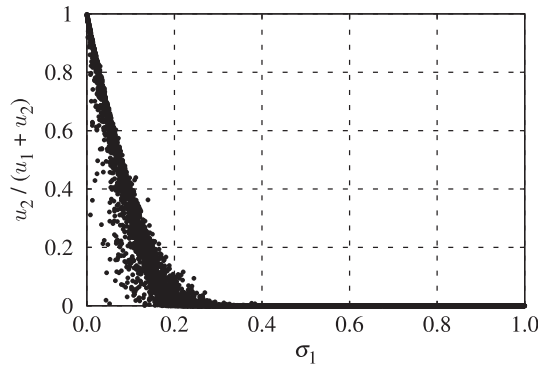


Fig. 5 Relationship between proportion of transferred power by packet 2 and density of packet 1 at $\langle e_1 \rangle_1 > \langle e_2 \rangle_2$.

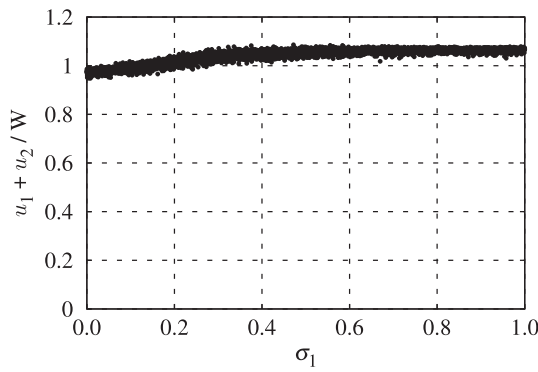


Fig. 6 Relationship between total amount of transferred power and density of packet 1 at $\langle e_1 \rangle_1 > \langle e_2 \rangle_2$. Only the results which satisfy $\sigma_1 + \sigma_2 > 0.3$ are plotted to ignore the voltage drop across the capacitor.

5. Concluding Remarks

This letter demonstrated the possibility of realizing the up-stream dispatching of required power to the sources by density modulation of power packet. The up-stream dispatching is adjustable at the router with power packets transferred through multiple inputs to the storage. The averaging method reveals the relationship between density of power packets and transferred power by the packets. By numerically simulating the dynamics of the router's storage, it is verified that the up-stream dispatching can be realized if the total density of inputted packets is set sufficiently large. Simulated results clearly show that even if the difference between voltages of packets is not small, the dispatching is realized by reducing the densities of packets with high voltage in transmission. These discussions provide a method for realizing desired supplies and demands by processing power by power packetization through electrical energy networks.

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