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Research Related to Power Packet and Its Application

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Abstract—In the Cross-ministerial Strategic Innovation Promotion Program (SIP), a project named "Next Generation Power Electronics" is ongoing. In the project, our group is figuring out the research towards power processing through the high frequency power switching and its applications. In this report, the outline and the target of the project is briefly explained.

1. Introduction

One of the research topics of the Cross-ministerial Strategic Innovation Promotion Program (SIP) is the project "Next Generation Power Electronics." Since 2014, 10 topics are on going in SIP. We have engaged in the feasibility study of "Research and development of low power and small size integrated power circuit and power processing technology based on applications of SiC power devices." This special session exhibits some results of the project and encourage researchers to approach nonconventional research filed with nonlinear thinking.

The project advances the applications of wide bandage semiconductors, SiC and GaM based on their physical superior characteristics. In particular, power electronics technology at the high frequency switching are not matured more than 10 MHz. The power switching in the range has not been well developed until the appearance of SiC and GaN power devices. In the range the power switching also shows the ability of the transfer of information.

Our group have proposed the new method of power transfer with information technology in the physical layer. Power is packetized as an unit and discretized power is transfer with each information tag. We call the technology of "power processing." In the following, we explains the concept of the power processing.

2. High Frequency Switching and Power Packet

Power electronics is the technology of converting waveform, quantity, or speed (frequency) on loads through the circuit switching . Then the voltage/current on loads are switched, so that the averaged voltage/current will be regulated according to the duty of switching rate. The ratings of the power devices govern the ability of the conversion. At the low frequency, inductors and capacitors, which are called storage passive devices, are inevitable for keeping continuous current and voltage. At the low switching frequency they becomes huge and they decides the size of the convertor circuits. From the view point of high power conversion, the passive devices also becomes huge.

Apparently, the high frequency switching makes it possible to deduce the size of the passive devices, because the power stored becomes low due to the intermittent duration. On the other hand, the switches show the physical limitation on the power rating, temperature limitation, and switching speed.

Recent development of wide bandage semiconductors changes the state of power switch. The show the possibility of power switching at the range of radio frequency, that is more than 10 MHz. They are enough to send information. At the sometime, the switch devices possess a capability of high current and the tolerance to high voltage with low on resistance.

Here we are proposing a system which transfer electric power at a pulse waveforms with an information-tags attached to the power. Needless to say, it becomes possible because of the appearance of the wide bandage semiconductors and their power devices.

3. Power Packetization and Processing

When electric power is packetized, total power is given by the accumulation of unit pulse power. The density of the packet changes the power density on time. This is a type of pulse density modulation (PDM). The method is completely different from PAM and PWM, which are analog conversion by switching. Their conversion depend on the duty in a time duration. However, PDM does not depend on the duty of pulse width, but the density of single pulse in a time duration. The density decides the power of the conversion.

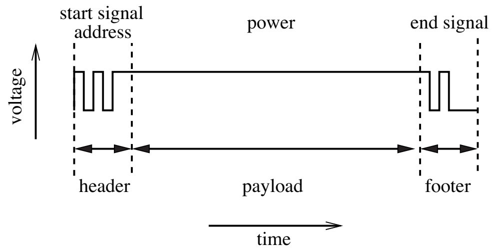

Figure 1: Power packet structure

As mentioned above, the power packet is accompanied by the tag. The information is tightly attached to physical power for each power unit [1][1]. The destination of their pulse power are decided according to the tag and the node devices, which are "mixer" and "router", are operated for sending and receiving. The synchronization of the router is also achieved by the preamble of tag. The network consisted of the routers are physical network of power transfer without tight physical connections between power sources and loads. Fig.2 is an example of the power packet dispatching network [2].

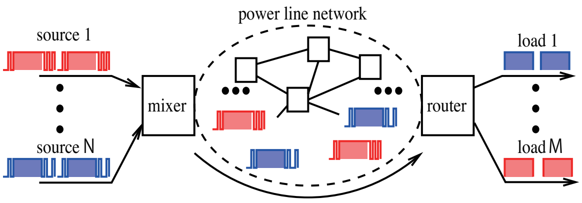

Figure 2: Power packet dispatching network

We have already discussed the system based on the communication theory ￥citeshannon and the differences are clearly shown [4].

4. Formulation of Power Packet Dispatching

The power packet is defined as a wave of power with information. As for the physical layer, various configurations are possible with keeping this concept. However, the substantial characteristic is that the power is quantized and transferred by the density distribution in a duration of time between two nodes. That is, power is digitized and quantized. In the quantized form, the spatially transferred power is decided between nodes [2]. In and out flow of power at a node corresponds to a density of packet. The deference of the densities implies the stored power at the node and loss. As for the link, the power is kept between nodes. We would like to represent the system based on the wave equation and quatum mechanics.

Here, we define the density (probability) of power packet by $\sigma_{\mathrm{n}}(t)$ at a node n in the s-th time duration $[t_{\mathrm{s}}, t_{\mathrm{s}} + \Delta t_{\mathrm{s}})]$, $v_{\mathrm{n}}(t)$ is set as the voltage of packet, and $i_{\mathrm{n}}(t)$ the current through the node by the packet. The energy $u_{\mathrm{n}}(\mathrm{s})$ is given in the duration by the following relation:

$$u_{\mathrm{n}}(\mathrm{s}) = \int_{t_{\mathrm{s}}}^{t_{\mathrm{s}}+\Delta t_{\mathrm{s}}} \sigma_{\mathrm{n}}(t) \cdot v_{\mathrm{n}}(t) \cdot i_{\mathrm{n}}(t)\mathrm{d}t. \quad (1)$$

Hereafter, the system is normalized by an appropriate base.

The total flow of power from the k-th node depends on the total flow into the node. The spatial node index is given by subscript. If there is no storage (buffer) at the node, the energy conservation law at t_{s} is represented by

$$\sum_{\mathrm{i}\in\{\mathrm{i}\to\mathrm{k}\}} u_{\mathrm{i}}^{\mathrm{k}}(\mathrm{s}) = \sum_{\mathrm{j}\in\{\mathrm{j}\leftarrow\mathrm{k}\}} u_{\mathrm{k}}^{\mathrm{j}}(\mathrm{s}). \quad (2)$$

The density of packet at k in a time duration implies the energy flow through k as follows:

$$u_{\mathrm{k}}(\mathrm{s}) = -\int_{t_{\mathrm{s}}}^{t_{\mathrm{s}}+\Delta t_{\mathrm{s}}} \sigma_{\mathrm{k}}(t) \cdot v_{\mathrm{k}}(t) \cdot i_{\mathrm{k}}(t)\mathrm{d}t. \quad (3)$$

Here, assume the single connection of nodes, then the energy flow by packets is defined between node k and (k + 1) as

$$u_{\mathrm{k}}^{\mathrm{k}+1}(\mathrm{s}) = -u_{\mathrm{k}+1}(\mathrm{s}) + u_{\mathrm{k}}(\mathrm{s}) \quad (4)$$

In the connection, $u_{\mathrm{k}}^{\mathrm{k}+1}(\mathrm{s}) = 0$ implies lossless line. Between nodes, the relationship holds:

$$u_{\mathrm{k}}^{\mathrm{k}+1}(\mathrm{s}) = -\int_{t_{\mathrm{s}}}^{t_{\mathrm{s}}+\Delta t_{\mathrm{s}}} \{\sigma_{\mathrm{k}+1}(t)\cdot v_{\mathrm{k}+1}(t)\cdot i_{\mathrm{k}+1}(t) - \sigma_{\mathrm{k}}(t)\cdot v_{\mathrm{k}}(t)\cdot i_{\mathrm{k}}(t)\}\mathrm{d}t, \quad (5)$$

The power packet is quantized in voltage. At the setting, $v_{\mathrm{k}+1}(\mathrm{s}) = v_{\mathrm{k}}(\mathrm{s})$. When $\sigma_{\mathrm{k}+1}(\mathrm{s}) = \sigma_{\mathrm{k}}(\mathrm{s})$, the transferred energy from node k to k + 1 at t_{s} becomes

$$u_{\mathrm{k}}^{\mathrm{k}+1}(\mathrm{s}) \sim -v_{\mathrm{k}}(\mathrm{s}) \int_{t_{\mathrm{s}}}^{t_{\mathrm{s}}+\Delta t_{\mathrm{s}}} \sigma_{\mathrm{k}}(t) \cdot \{i_{\mathrm{k}+1}(t) - i_{\mathrm{k}}(t)\}\mathrm{d}t. \quad (6)$$

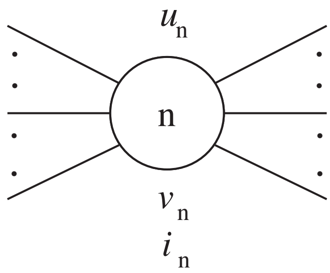

Figure 3: Node and state.

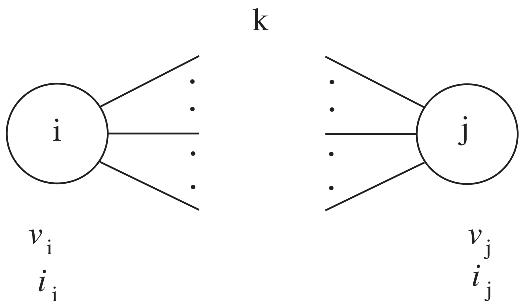

Figure 4: Node connections.

[1] If the information is apart from payload (power), the power must be measured and lose the physical meaning except the amount.

[2] Wave equation is a form of relationship in neighboring elements. Single power packet, which corresponds to a quantized power, is exactly a wave between nodes. The relationship does not include the long distance over the next node.

The relationship implies that the the energy between nodes depends on the current through the neighboring loop.

$$\sigma_{\mathrm{k}} = \int_{t_s}^{t_s+\Delta t_s} \sigma_{\mathrm{k}}(t)\mathrm{d}t \tag{7}$$

gives the temporal rate of packet.

The total energy of the system is given by $U(\mathrm{s})$. It normalizes the system as

$$j_{\mathrm{k}}^{\mathrm{k+1}}(\mathrm{s}) = -\frac{u_{\mathrm{k}}^{\mathrm{k+1}}(\mathrm{s})}{U(\mathrm{s})} \sim \frac{A\sigma_{\mathrm{k}}}{K} v_{\mathrm{k}}(\mathrm{s}) \cdot \{i_{\mathrm{k+1}}(\mathrm{s}) - i_{\mathrm{k}}(\mathrm{s})\} \tag{8}$$

Here A is the normalizing coefficient and K the coupling inductance. The Γ-shaped radder connection of L and C is the unit element of distribution line. Then,

$$i_{\mathrm{k+1}}(\mathrm{s}) - i_{\mathrm{k}}(\mathrm{s}) = v_{\mathrm{k}}(\mathrm{s}) \cdot \mathrm{i}\omega C.$$

Here the current can be replaced by voltages of nodes. Real value v_{k} can be replaced by complex value with the complex conjugate voltage $v_{\mathrm{k}}^{c} + v_{\mathrm{k}}^{c*}$. And the current

$$\begin{aligned} j_{\mathrm{k}}^{\mathrm{k+1}}(\mathrm{s}) \quad \sim \quad & \frac{\mathrm{i}\omega CA\sigma_{\mathrm{k}}}{K}(v_{\mathrm{k}}^{c}(\mathrm{s}) + v_{\mathrm{k}}^{c*}(\mathrm{s}))\{(v_{\mathrm{k}}^{c}(s) - v_{\mathrm{k+1}}^{c}(\mathrm{s})) \\ & -(v_{\mathrm{k}}^{c*}(\mathrm{s}) - v_{\mathrm{k+1}}^{c*}(\mathrm{s}))\} \end{aligned} \tag{9}$$

5. Remarks

This paper summarizes the engineering and mathematical basis of the research supported by SIP project. The idea of power processing has already been proposed in several research project, including NICT project and Super Cluster Program, with achievement of power packetization in the physical layer. The conventional power transfer completely included in the formulation of power packet dispatching. The each power sources faces to another types of dynamics with combination to ICT.

In the packetized power transfer, the optimization of the packet distribution and flow control will be an important target in the next step. The realization of system completely depends on the development of power devices and their circuit implementations at high frequency switching range.

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