Single-Inductor Multiple-Source Mixer for DC Power Packet Dispatching System

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***Abstract*—DC power packet dispatching system is reported recently aiming to deliver power in a packet form. It can utilize less power conversion stages which increases power distribution efficiency and monitor load demand intelligently from source side to keep the system stable. A multiple-energy-source mixer based on a multiple-input single-inductor buck converter for DC power packet dispatching system is proposed. It is capable of generating power packets at different voltage levels by time sharing of multiple power sources. In this work, three different sources including a PV panel and two DC voltage sources are used for the power packet dispatching system. A control strategy is devised in order that the PV panel can track maximum power point (MPP) approximately and the PV is given a priority to share power in each power packet generation. Experimental results are reported to verify the proposed mixer and its control strategy for DC power packet dispatching system.**

***Index Terms*—Power packet, multiple-energy-source mixer.**

I. Introduction

Recently reported DC power packet dispatching system enables power to be delivered in a packet form to the loads [1], [2], [3], [4]. In the reported power packet delivery system, it is not compulsory to convert renewable energy sources (RESs) voltage to a unified voltage level which is one of the main advantages of the power packet transmission system [1], [4], [5], where each power packet generation is limited to one source per power packet in these articles reported. Nevertheless, the absence of an intermediate voltage conversion stage increases the efficiency of the overall power system. Also this system can eliminate the control issues related to the parallel connected converters as RESs will not be connected to the distribution line at the same time. Loads are always being isolated from the main distribution line until it receives the payload upon requested.

A power packet dispatch system consists of a router and a mixer. In the power packet dispatch system, the DC power is converted to a pulse power. Attaching an information tag to the power packet is used to distribute and identify the payload to the designated load. A mixer is used to generate a power packet and send it to the router through a transmission line. After receiving the power packets, the router sends the power packets to the objective loads [6], [7].

For the mixer reported in [4], [8], the payload in each time can be generated only from a single source. However, if the power packets are intended to be generated in this reported system by more than one source at different voltage levels, the power packet will be of irregular shapes, i.e. the voltage regulation at load side is lost. To overcome this problem, we proposed a new structure by using a multiple-input buck converter to mix different sources and using its internal output filter to smooth the power packet voltage. It is capable of sharing power from preferred renewable energy sources in each power packet generation to extract maximum power. It can be helpful to utilize more renewable energy rather than conventional energy.

II. Power Packet Dispatch System

In the power packet distribution scheme, each load will receive power in a packet form. Each power packet contains an electronic tag information of the supplying source, loads and payload which is the actual power to be transferred to the objective loads. The structure of the electronic tagging reported in [6] uses a header which consists of information of the power packet start signal, source and load identities, and a footer. The footer is used mainly to notify the router about the end of a power packet transmission [6]. The power packet structure proposed in [6] is shown in Fig. 1. Information tags can be attached electrically to the payload. Time division multiplexing (TDM) is used to prevent payloads overlapping. A mixer is responsible for power packet generation for the requested loads and power packet distribution to the designated loads is done by the router. An extra communication channel can also be used to exchange demand and routing information. The mixer structure reported in [4] is shown in Fig. 2. In the reported scheme each power packet can only be generated from a single source. If a power packet is intended to be generated in this reported system by sharing power from more than one source then the voltage of the generated power packet will not be smooth. The mixer structure proposed in this paper given in Fig. 3 can generate power packets by sharing power from more than one source where each power packet voltage is smooth according to the demand. In addition, preference can be given to any source if we want to extract and utilize maximum power from any RES.

III. Operation Principle of Proposed Mixer

The operation principle of the proposed mixer which is used to generate two power packets with different voltage levels

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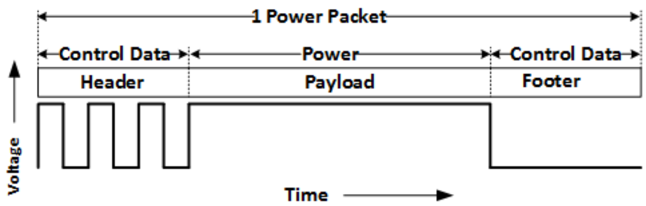


Fig. 1. Structure of a power packet [6].

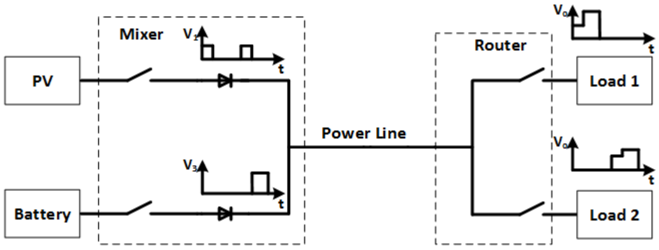


Fig. 2. Power packet dispatching system using the mixer reported previously in [4] which cannot generate power packet by sharing power from more than one source.

using the available power and energy sources is explained as follows. The diagram of the proposed mixer circuit diagram used in the experiement is given in Fig. 4. The MPP voltage of the used PV panel is V_1(12V). Voltage level of the power sources are chosen as V_2(15V) and V_3(36V) which are some common voltage rating of the renewable energy sources. 24V and 12V are selected in the experiment as power packet voltages (V_o) as these are the some common voltages of the DC loads. Power sources having voltage ratings other than aforementioned can also be used to generate power packet at different voltage levels as long as it satisfies $V_o \in [0, max(V_1, V_3)]$.

A. 24V Payload Generation

In this operation mode, two input power sources V_1 (PV) and V_3 are responsible for 24V power packet generation. In this mode, S_2 is turned off always and S_1 and S_3 are active. For each switch a specific duty ratio is considered. S_1 regulates the input voltage accross the PV to attain MPPT. The output voltage is controlled by S_3 while generating 24V

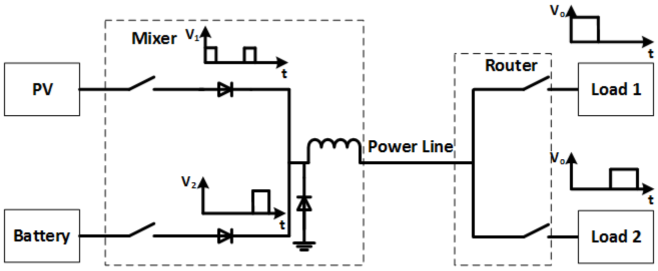


Fig. 3. Power packet dispatching system using the proposed mixer which can generate power packet by sharing power from more than one source and also preference can be given to any source in each power packet generation.

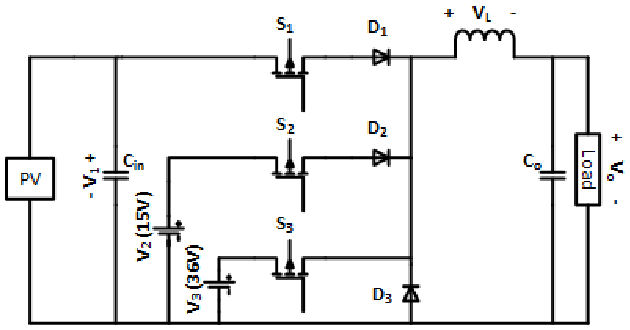


Fig. 4. Mixer circuit diagram used in the experiment.

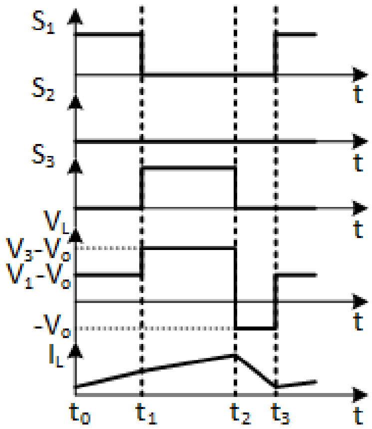


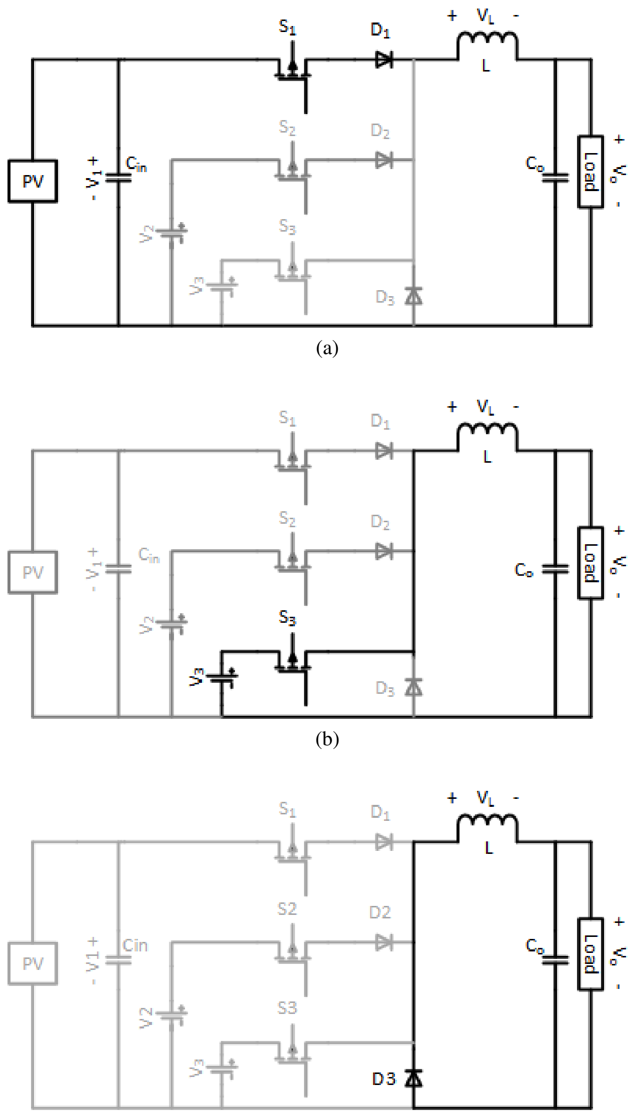
Fig. 5. Steady state waveforms while generates 24V power packet.

power packet. Gate signals of the switches and also voltage and current waveforms of the inductor are shown in Fig. 5. According to switching states, there are three different switching states in one switching period as follows:

1) Switching State 1 ($t_0 < t < t_1$): In this mode, switch S_1 and S_3 are turned on and turned off respectively. Diode D_1 is forward biased and diode D_3 is reverse biased. The equivalent circuit of the proposed mixer in this state is shown in Fig. 6(a). In this mode, the PV charges inductor L, hence the inductor current increases. Also the output capacitor C_o is charged in this mode.

$$\left.\begin{aligned} C_{in}\frac{dv_1}{dt} &= i_{ph} - i_L \\ C_o\frac{dv_o}{dt} &= i_L - \frac{v_o}{R} \\ L\frac{di_L}{dt} &= v_1 - v_o \end{aligned}\right\} \quad (1)$$

2) Switching State 2 ($t_1 < t < t_2$) : In this state, switch S_3 is turned on and switch S_1 is turned off concurrently. Diodes D_1 and D_3 are reverse biased. The equivalent circuit of the proposed mixer in this state is presented in Fig. 6(b). In this mode, V_3 charges inductor L, hence the inductor current increases. Also the output capacitor



(a) (b) (c)

Fig. 6. Equivalent circuit while generates 24V power packet, (a) switching state 1, (b) switching state 2, (c) switching state 3.

C_o is charged in this state.

$$\left.\begin{aligned} C_{in}\frac{dv_1}{dt} &= i_{ph} \\ C_o\frac{dv_o}{dt} &= i_L - \frac{v_o}{R} \\ L\frac{di_L}{dt} &= v_3 - v_o \end{aligned}\right\} \tag{2}$$

3) Switching State 3 $(t_2 < t < t_3)$: In this mode, switches S_1 and S_3 are turned off. Hence, diode D_3 is forward biased. The equivalent circuit of the proposed mixer in this mode is shown in Fig. 6(c). In this mode, the inductor L is discharged and delivers its stored energy to output capacitor C_o and load resistance. Hence the inductor current decreases and the output capacitor C_o is charged.

$$\left.\begin{aligned} C_{in}\frac{dv_1}{dt} &= i_{ph} \\ C_o\frac{dv_o}{dt} &= i_L - \frac{v_o}{R} \\ L\frac{di_L}{dt} &= -v_o \end{aligned}\right\} \tag{3}$$

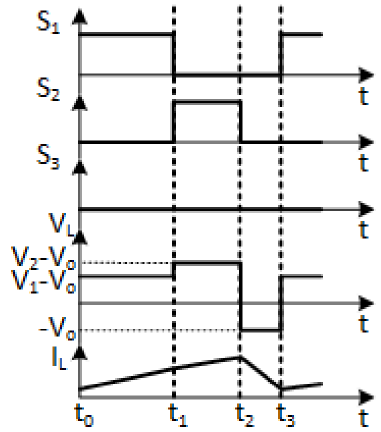


Fig. 7. Steady state waveforms while generates 12V power packet.

B. 12V Payload Generation

In this operation mode, two input power sources V_1 (PV) and V_2 are responsible for 12V power packet generation. In this mode, S_3 is turned off entirely and S_1 and S_2 are active. For each switch a specific duty cycle is considered. S_1 regulates the input voltage across the PV to attain MPPT. The 12V output voltage is controlled by S_2. Gate signals of the switches and also voltage and current waveforms of the inductor are shown in Fig. 7. According to the switching states, three different switching states can be found in one switching period as follows:

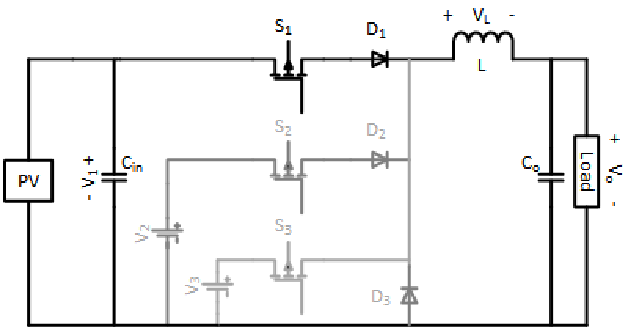
1) Switching State 1 $(t_0 < t < t_1)$: In this mode, switch S_1 is turned on and S_2 is turned off. Diode $D_1$is forward biased and diode D_3 is reverse biased. The equivalent circuit of the proposed mixer in this state is presented in Fig. 8(a). In this mode, the PV charges inductor L, hence the inductor current increases. Also the output capacitor C_o is charged in this mode.

$$\left.\begin{aligned} C_{in}\frac{dv_1}{dt} &= i_{ph} - i_L \\ C_o\frac{dv_o}{dt} &= i_L - \frac{v_o}{R} \\ L\frac{di_L}{dt} &= v_1 - v_o \end{aligned}\right\} \tag{4}$$

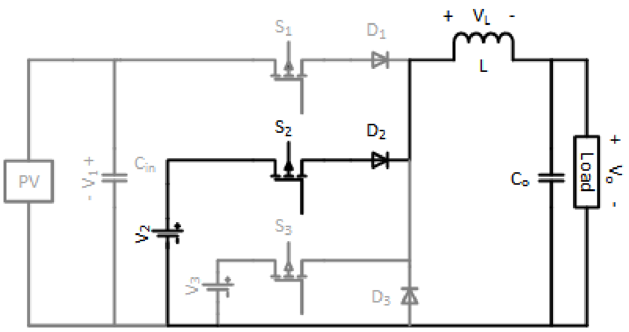
2) Switching State 2 $(t_1 < t < t_2)$: In this state, switches S_1 and S_2 are turned off and turned on respectively. Diode D_1 and D_3 is reverse biased. The equivalent circuit of the proposed converter in this state is shown in Fig. 8(b). In this mode, V_2 charges inductor L, hence the the inductor current increases. Also the output capacitor C_o is charged in this state.

$$\left.\begin{aligned} C_{in}\frac{dv_1}{dt} &= i_{ph} \\ C_o\frac{dv_o}{dt} &= i_L - \frac{v_o}{R} \\ L\frac{di_L}{dt} &= v_2 - v_o \end{aligned}\right\} \tag{5}$$

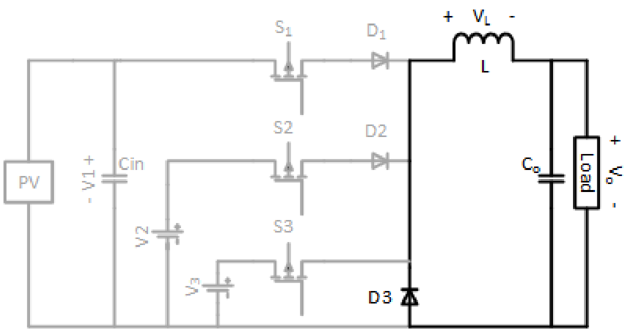
3) Switching State 3 $(t_2 < t < t_3)$: In this mode, switches S_1 and S_2 are turned off. Hence, diode D_3 is forward biased. The equivalent circuit of the proposed mixer in this mode is shown in presented in Fig. 8(c). In this



(a)



(b)



(c)

Fig. 8. Equivalent circuit while generates 12V power packet, (a) switching state 1, (b) switching state 2, (c) switching state 3.

mode, inductor L is discharged and delivers its stored energy to output capacitor C_o and load resistance. Hence the inductor current decreases and the output capacitor C_o is charged.

$$\left.\begin{aligned} C_{in}\frac{dv_1}{dt} &= i_{ph} \\ C_o\frac{dv_o}{dt} &= i_L - \frac{v_o}{R} \\ L\frac{di_L}{dt} &= -v_o \end{aligned}\right\} \tag{6}$$

IV. Experimental Results

The mixer circuit with three inputs for low power application is built to verify the proposed power packet generation system. The schematic diagram of the experiemental setup is given in Fig. 9. Circuit parameters used in the experiment are as follows: V_1 = voltage at MPP of PV panel (12V), V_2 = 15V, V_3 = 36V, L = 0.1mH, C_{in} = 470µF, R = 10Ω, K_{p1} = K_{p2}= K_{p3} = 5, K_{i1} = K_{i2} = K_{i3} = 1000, modulator gain F_m = 0.4. Power packets of 24V and 12V rating are being generated in the experiment. It is been considered in the experiment that power packets of two different voltages requested by the load alternately. Hence the same resistive load (R = 10Ω) is used for the 24V and 12V power packet generations. A PWM controller IC SG 3525 is used to implement the input voltage control across the PV and the output voltage regulation while generating power packet. The PV module is artificially lit by three halogen lamps. An approximate MPPT method using a PI controller for fixed PV voltage is adopted in this paper. A simple analog PWM controlller is used in the experiment to control the voltage across the PV. The switching frequency used in the experiment is 90kHz. The power packets generated at 24V and 12V are shown in Fig. 10. We have assumed that voltage sources V_2 and V_3 will contribute to generate the power packet of 12V and 24V rating respectively. The PV will contribute in each power packet generation untill it satisfies the voltage rating. Hence, each power packet will be generated by sharing power from the PV and any of the power source.

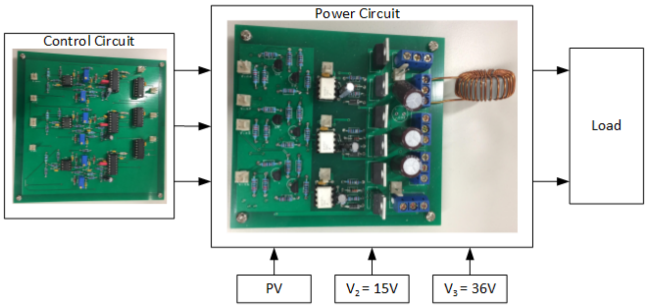


Fig. 9. Experimental setup schematic.

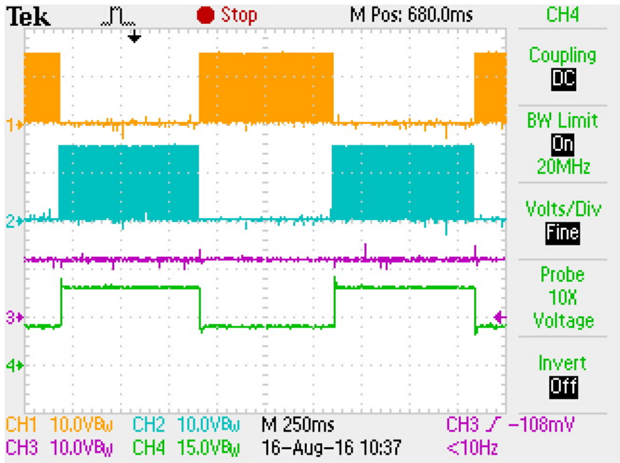


Fig. 10. Power packet generation of having 24V and 12V rating (CH1and CH2 - switching signal of switch 2 and 3 respectively, CH3 and CH4 - controlled voltage across PV to achieve approximate MPPT and generated power packet of 24V and 12V rating respectively).

In Fig. 10, it can be seen that there is no switching signal in S_2 while generating 24V power packet shown in CH4 and

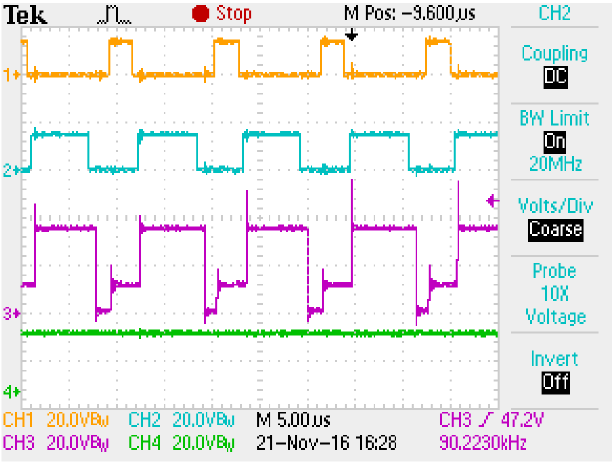


Fig. 11. Enlarged view of the 24V power packet generation (CH1 and CH2 - switching signal of switch S_1 and S_3 respectively, CH3 - voltage before the internal filtering while generating 24V power packet, CH4 - voltage of generated power packet of 24V).

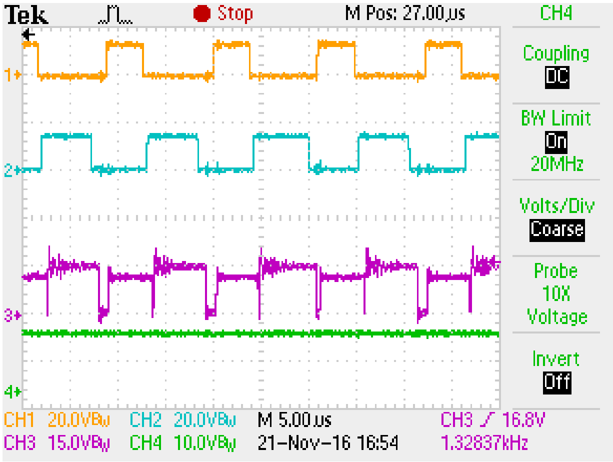


Fig. 12. Enlarged view of the 12V power packet generation (CH1 and CH2 - switching signal of switch S_1 and S_2 respectively, CH3 - voltage before the internal filtering while generating 12V power packet, CH4 - voltage of generated power packet of 12V).

also there is absence of switching signal in S_3 during 12V power packet generation presented in CH4. From CH3 it can be also seen that the voltage across the PV is maintained at 12 V to achieve the approximate MPPT. From the enlarged view of the of the generated 24V power packet shown in Fig. 11, it can be seen that the PV contributes power with the voltage source V_3 in the 24V power packet generation. The voltage waveform before the inductor filtering is of irregular shapes while generating 24V power packet and the proposed mixer generates smooth 24V power packet using its internal filter.

Similarly, Fig. 12 shows that the internal filtering in the proposed mixer can generate smooth 12V power packet while the voltage waveform before the inductor filtering is of irregular shape. From both cases it is clearly seen that the PV contributes in each power packet while the voltage across the PV is controlled at MPP. From Figs. 11 and 12, it can also be seen that duty cycle of switching signal of S_1 is larger while generating 12V power packet rather than 24V power packet. While generating 12V power packet, the PV shares more energy than in 24V power packet generation.

Hence it is experimentally proved that the proposed mixer can generate power packets by sharing power from more than one source.

V. Conclusion

A mixer for a power packet generation system which uses a single inductor multiple-input single-output converter is proposed in this paper. It is capable of power packet generation by sharing power from more than one power or energy source. A control scheme is proposed which can program to give preferences to the PV source in this design in each power packet generation. An analog PI controller is used to stablize the output voltages. As the PV is used as a power source hence a PI controller is also used to regulate the voltage across the PV to achieve the approximate MPPT which is sufficient to demonstrate the proposed source mixing feature while achieving voltage regulation and power conditioning simultaneously. A hardware prototype has been built and experimentally verified the proposed mixer structure. Thanks to the internal filtering of the proposed mixer which smoothes out and regulates each power packet (was of irregular shape when mixing) to reach the correct voltage level before sending through the channel. Hence the proposed mixer structure and control scheme can generate power packet at different voltage rating and also more than one source can contribute in each power packet generation. Power sharing capability and giving priority to share power to any source in each power packet generation can help to utilize more available renewable energy.

References

[1] T. Takuno, M. Koyama, and T. Hikihara, "In-home power distribution systems by circuit switching and power packet dispatching," in *First International Conference on Smart Grid Communications (SmartGridComm)*. IEEE, 2010, pp. 427–430.

[2] H. Sugiyama, "Pulsed power network based on decentralized intelligence for reliable and lowloss electrical power distribution," *Journal of Artificial Intelligence and Soft Computing Research*, vol. 5, no. 2, pp. 97–108, 2015.

[3] R. Takahashi, K. Tashiro, and T. Hikihara, "Router for power packet distribution network: Design and experimental verification," *IEEE Transactions on Smart Grid*, vol. 6, no. 2, pp. 618–626, 2015.

[4] R. Takahashi, S. i. Azuma, and T. Hikihara, "Power regulation with predictive dynamic quantizer in power packet dispatching system," *IEEE Transactions on Industrial Electronics*, vol. PP, no. 99, pp. 1–1, 2016.

[5] V. Krylov, D. Ponomarev, and A. Loskutov, "Toward the power intergrid," in *IEEE International Energy Conference and Exhibition (EnergyCon)*. IEEE, 2010, pp. 351–356.

[6] C. M. F. S. Reza and D. D. C. Lu, "Improved power routing algorithm for power packet distribution system," in *2016 IEEE 5th Global Conference on Consumer Electronics*, Oct 2016, pp. 1–2.

[7] K. Tashiro, R. Takahashi, and T. Hikihara, "Feasibility of power packet dispatching at in-home dc distribution network," in *Third International Conference on Smart Grid Communications (SmartGridComm)*. IEEE, 2012, pp. 401–405.

[8] R. Takahashi, S.-i. Azuma, K. Tashiro, and T. Hikihara, "Design and experimental verification of power packet generation system for power packet dispatching system." in *ACC*, 2013, pp. 4368–4373.