

# Letters

## Coded Power Transfer

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**Abstract**—This letter captures in brief a core innovation in the two patented technologies. The underlying focus of the two technologies is to demonstrate how discrete energy transfer can be achieved that leads enhanced power-conversion efficiency in one case and a mechanism for packetized energy transfer that can enable cotransfer of information and energy.

**Index Terms**—Coding, converter, discrete, energy, modulation, packet.

### I. INTRODUCTION

**P**OWER-ELECTRONIC systems, including but not limited to solid-state transformers, indirect matrix converters, galvanically isolated electric-vehicle chargers, and high-frequency-link (HFL) converters, often have multiple stages of power conversion. Usually, switching of the devices of each of these power-conversion stages follow some modulation principle(s) that yields desired goal(s). Often, the information generated in the pulsating intermediate power signals are lost due to intermediate filtering (e.g., dc link) that lands up requiring additional switching or forced commutation. For one such HFL power-conversion system, a novel technology, referred to as hybrid modulation [1], [2], [3], was captured, which provides a unique mechanism of utilizing the “coded” information in the switching power signal due to modulated switching of the power semiconductor devices, thereby reducing switching losses and eliminating the need for dc-link capacitors and yielding reduced form factor. This is briefly illustrated in Section II.

While the hybrid modulation enables the coded power transfer in a multistage but typically single overall power-conversion system, another approach, as outlined in Section III, relates to the

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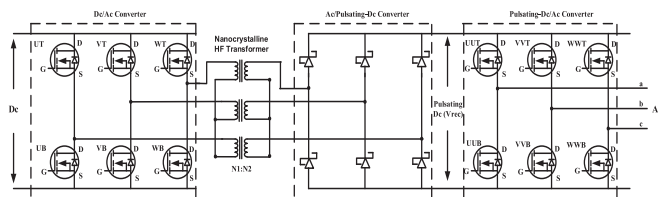


Fig. 1. Topology of a capacitorless pulsating-DC-link HFL inverter.

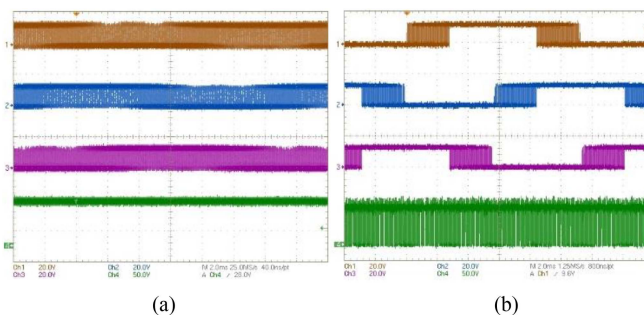


Fig. 2. Experimental illustration. (a) PWM signals of a conventional fixed-DC-link inverter that requires HF switching of all legs of the output stage since the coded information is lost in the DC link. (b) Hybrid modulation, instead, requires switching of only one leg at HF since the pulsating-DC link retains the sinusoidally modulated information coded by the first stage. It is referred to as hybrid modulation because of (and unlike conventional) discontinuous modulation while one output stage operates at HF, and the other two stages at low frequency.

transfer of discretized energy transfer among distributed power converters [4], [5]. Basically, in an embodiment, each power converter generates energy packets that are cotransferred with information in a mutually exclusive sequential manner. This is fundamentally different from relatively recent approaches where the same converter is used for energy and data transfer by leveraging the modulation of the converter [6]. The proposed approach achieves high baud rate since the data transfer is not at high voltage and, hence, not limited by the capacitance of the power semiconductor device. Because the data and the energy packets are mutually exclusive in one embodiment of the proposed approach, possibility of interference is essentially eliminated. By generating such discretized energy packets transmitted at high frequency (with appropriate coding) for an energy receiver or a set of energy receivers, applications, such as distributed energy storage, can reduce size and weight of systems or the overall efficiency of a network could be improved.

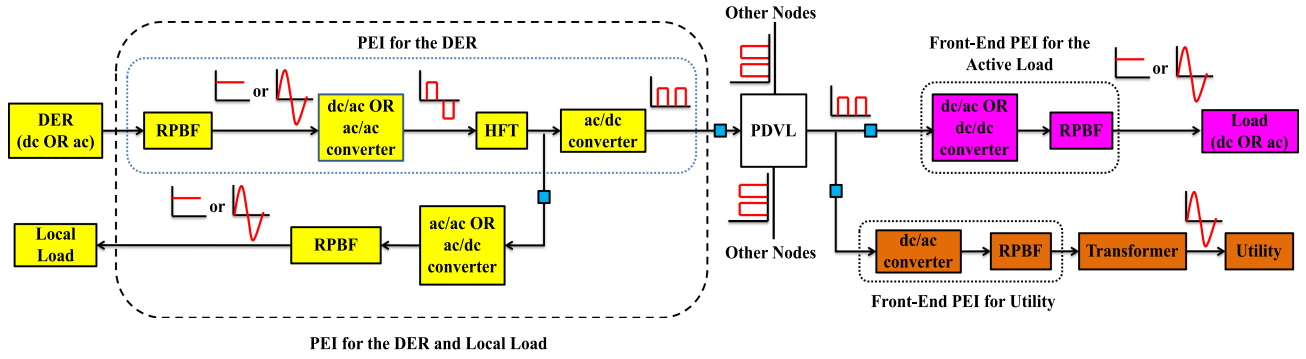


Fig. 3. Illustrative power-electronic-interface (PEI) mechanism for creating a pulsating-DC-voltage-link (PDVL) leading to an illustrative SIMO realization. The PDVL is illustrated in Fig. 4. Also illustrated are the PEIs for the distributed energy resource (DER) and the local load, distributed load, and the utility grid. Voltage signals at different stages are shown in red. It is noted that, power flow can be bidirectional depending on a load or a DER even though not explicitly shown. RPBF represent the ripple power balancing filter, while HFT represents that the high-frequency transformer, which may be necessary, in isolation is needed.

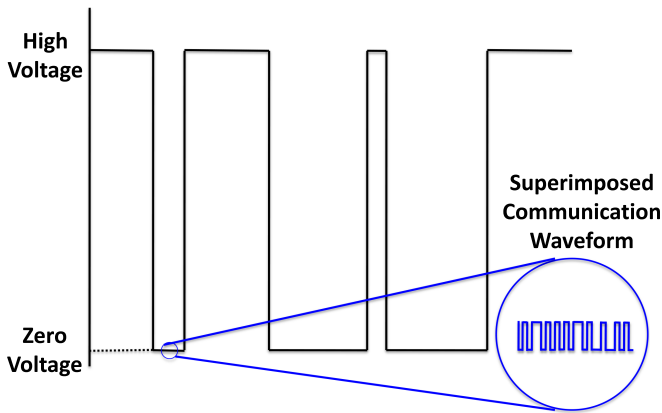


Fig. 4. Illustration of the PDVL in Fig. 3 supporting discrete energy and data for a Boolean realization.

## II. HYBRID MODULATION OF HFL INVERTER

Fig. 1 [2] shows capacitorless pulsating-dc-link HFL inverter. In this topology, the dc input is first converted into an HF ac, then rectified, and then converted to a sinusoidal pulsewidth modulation (PWM) signal for the three-phase output. What is novel in this approach is that the information that is “coded” in the first stage (i.e., HF inverter) of the overall HFL inverter is never lost unlike a conventional fixed-dc-link or unfolding-link inverter (which requires HF switching of the final stage). Instead, the final stage of the overall HFL inverter simply uses the coded pulse sequence available at the pulsating-dc link to generate the needed sinusoidally modulated switching signals simply by switching (for any  $60^\circ$  sector) only one of the legs at HF, while the other two legs do not change their switching states. This reduces the switching loss of the final stage by 66% without requiring any complex soft switching and any large dc-link capacitor. This is illustrated in Fig. 2 [2].

Additional work has shown that if the coding of the front-stage HF inverter is so done such that it not only generates sinusoidally modulated power signals but also leverages pulse placement, then, additional improvement in input current total harmonic distortion (THD) can be achieved [7] due to this

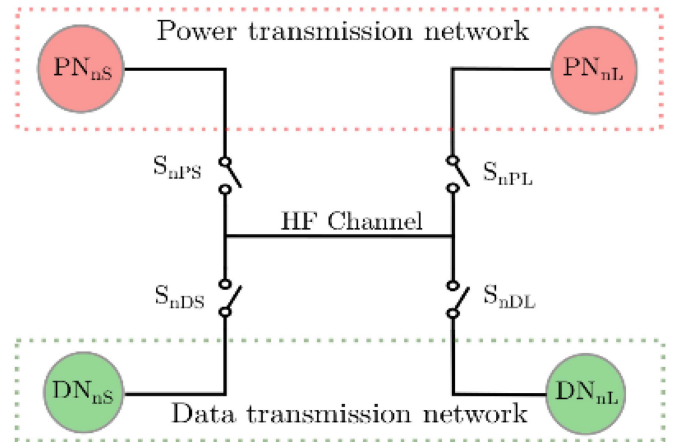


Fig. 5. Illustrative realization of the mutually exclusive power and data transfer.

two-dimensional modulation scheme that generates a different coded power-signal pattern. Yet another work has demonstrated if the front-end inverter has a V6 topology (instead of the V3 topology or one with three bridges, as shown in Fig. 1), then, even the remaining 33% switching loss of the final stage of the HFL inverter can also be eliminated [3]. This is achieved by generating two time-staggered pulse sequence at the output of the front-end HF inverter, which ensures the availability of the complete coded information at the pulsating-dc link and eliminates the need for any HF switching for the final HFL inverter stage, thereby yielding 100% switching loss elimination.

Since its inception, the hybrid-modulation-based inverter has found application in solar- and fuel-cell inverters, solid-state transformer, and electric-vehicle fast battery charger.

## III. BOOLEAN ENERGY GRID

The question now arises, what happens if the pulsating-dc link, as outlined in Section II, is not terminated in only one final stage converter? Can it be fed to multiple such output stages with some front-end routing if necessary. The answer to that is a yes for such a single-input single-output (SISO) or single-input multiple-output (SIMO) realizations, as illustrated

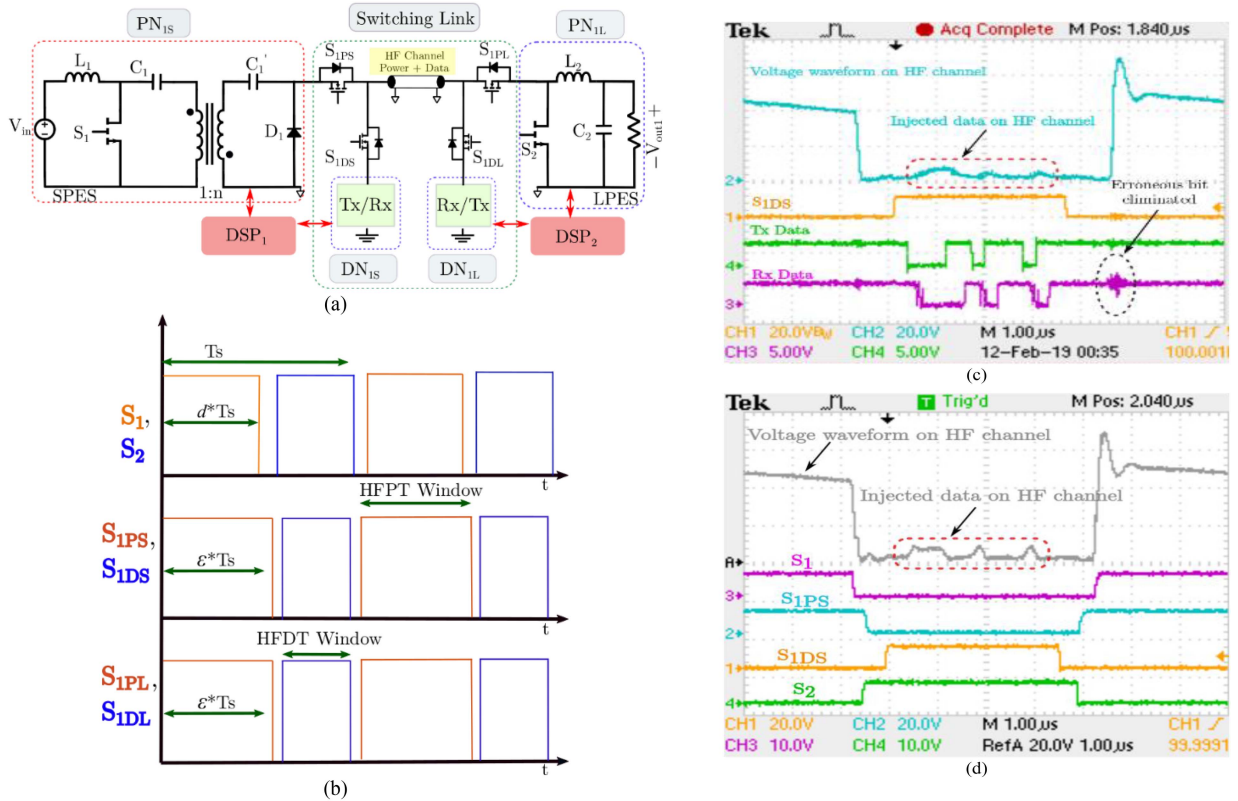


Fig. 6. (a) SISO HFDPS for implementing Boolean power and data transfer. Operational details are provided in [9]. (b) Timing diagram of key switches. (c) and (d) Experimental result showing the efficacy of the Boolean power and data transfer.

in Fig. 3. In fact, one can generalize the idea to even a multiple-input single-output (MISO) or multiple-input multiple-output (MIMO) realization [4], [5].

The advantage that was realized for a single pulsating-dc-link HFL inverter, as outlined in Section II, can now be extended to an entire network of power-electronic systems. Unlike the conventional dc and 60/50 Hz ac energy transfer, with continuous energy transfer, in this new approach, discretized energy is transferred from single or plural energy source(s), such as information data packets in communication systems, which can be routed to single or multiple energy sink(s) or loads. An illustrative advantage embodiment is that, since the discretized energy is sent in fast but with smaller energy packets, the distributed energy storage requirements can be reduced significantly. Furthermore, the energy packets can be coded in such a way (following Section II) such that downstream switching requirements could be reduced thereby yielding higher efficiency. Furthermore, since the energy packets are discretized, they themselves can be coded (e.g., placing the pulses at different temporal location in a periodic cycle) to convey information for downstream converters yielding additional advantages including but not limited to security.

Yet another major advantage of the discretized energy transfer implies that when energy is not being transferred, the data can be transferred rapidly over the same channel since there is no high-voltage signal at that instant on the PDVL, as shown in Fig. 3. This implies that one can now realize a Boolean energy grid

where discretized energy and data can be transmitted mutually exclusively, as illustrated in Fig. 4.

The illustrative synthesis of the mutually exclusive realization is captured in Fig. 5. It shows how the  $n$ th source-side power node (PN<sub>nS</sub>) transfers energy to the  $n$ th load-side power node (PN<sub>nL</sub>) over a common HF channel if only the routing switches  $S_{nPS}$  and  $S_{nPL}$  are simultaneously activated. During this time, the data network is inactive. This synchronization of  $S_{nPS}$  and  $S_{nPL}$  is achieved by pretransferring information over the data network from the source-side data-network node  $DN_{nS}$  to the load-side data-network node  $DN_{nL}$  over the common channel. During this time, only  $S_{nDS}$  and  $S_{nDL}$  are simultaneously activated and  $S_{nPS}$  and  $S_{nPL}$  are turned OFF. It is noted that the information transferred over the data network is not limited to synchronization information. The mutual exclusivity of energy and information ensures limited or no coupling, as demonstrated in [5].

Since its inception, this concept has been explored for solid-state lighting, distributed energy storage, and Boolean microgrid.

#### A. SISO Realization

Fig. 6 captures an experimental snapshot that validates the operation of this Boolean energy and information transfer mechanism. The schematic of the SISO HF distributed power system (HFDPS) is captured in Fig. 6(a) along with timing diagram in

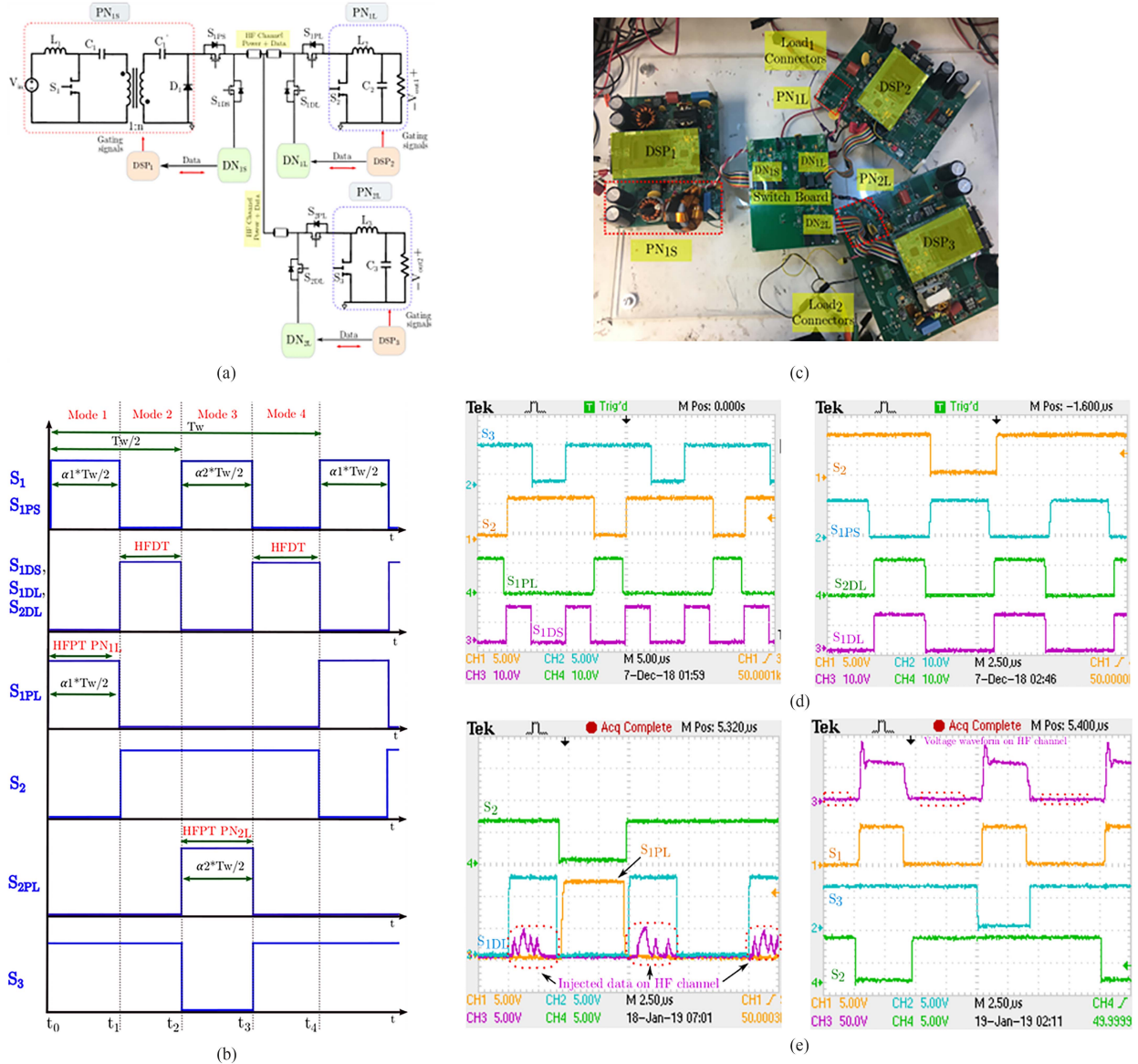


Fig. 7. (a) SIMO HFDPS for implementing Boolean power and data transfer and the (b) associated timing diagram. (c) Experimental SIMO HFDPS setup and (d) associated gating signals, and (e) experimental waveforms showing the transfer of HF data signals over the HF channel, along with the gating signals for  $S_{1DL}$ ,  $S_{1PL}$ , and  $S_2$  at  $PN_{1S}$ , and experimental waveform showing sequential cotransfer of HF power and data over the HF channel in a SIMO HFDPS along with the gating signals for  $S_1$ ,  $S_3$ , and  $S_2$ .

Fig. 6(b) (illustrating HF power and data transfer (HFPT/HFDT) windows over a time horizon  $T_s$ ) and the details are provided in [9]. In Fig. 6(c), to the left and right of the waveform, power is being transferred as indicated by higher voltage on the HF channel and  $S_{1DS}$  toggling to a low state. Once  $S_{1DS}$  toggles high, the data transfer over the same HF channel is initiated, while power transfer is disabled.

### B. SIMO Realization

A SIMO HFDPS realization is illustrated in Fig. 7.  $PN_{1S}$  serves as the source power node, while  $PN_{1L}$  and  $PN_{2L}$  serve as the two load nodes. Power nodes  $PN_{1S}$ ,  $PN_{1L}$ , and  $PN_{2L}$  and data nodes  $DN_{1S}$ ,  $DN_{1L}$ , and  $DN_{2L}$  are connected to the HF channel using transfer switches  $S_{1PS}$ ,  $S_{1PL}$ , and  $S_{2PL}$  and data switches  $S_{1DS}$ ,  $S_{1DL}$ , and  $S_{2DL}$ , respectively.

Consistent with a SISO HFDPS, in a SIMO HFDPS following sequential cotransfer scheme, transfer and data switches are operated in a mutually exclusive manner. Each combination of a power node and its corresponding data node is managed using a separate digital controller  $DPS_1$  or  $DSP_2$ .

$DSP_1$  coordinates locally with  $PN_{1S}$  for gating signals and feedback signals,  $DN_{1S}$  regarding data communication and mode selection and switching link regarding sequential power and data cotransmission. Similar roles are performed by  $DSP_2$  and  $DSP_3$  for power nodes  $PN_{1L}$  and  $PN_{2L}$ , data nodes  $DN_{1L}$  and  $DN_{2L}$ , and the switching link. When working together, the coded data are exchanged between the data nodes, and power packets generated by  $PN_{1S}$  are routed to  $PN_{1L}$  and  $PN_{2L}$  following the time-division multiplexing (TDM).

Timing diagram of the SIMO HFDPS is shown in Fig. 7(b). In it,  $T_w$  represents the time duration of a TDM frame required

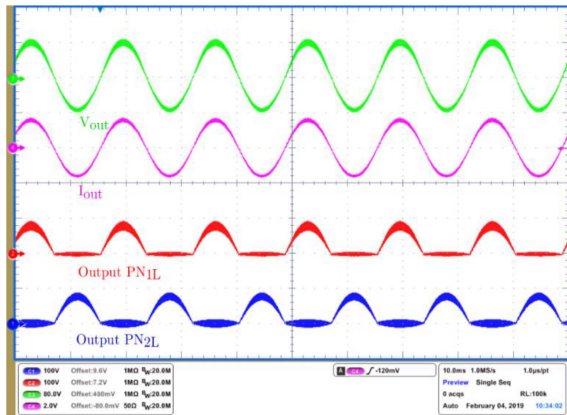


Fig. 8. Results for a SIMO HFDPS with the two load nodes connected in a differential-mode configuration.

for routing HF power and data packets in the designed SIMO HFDPS. Since in the designed SIMO HFDPS, HF power packet needs to be routed to the two LPES, and the TDM frame is subdivided in two equal time slots each with a duration of  $T_w/2$ . During the time interval  $t_0-t_1$ , the HF power packet is routed from  $PN_{1S}$  to  $PN_{1L}$  and during the time interval  $t_2-t_3$ , HF power packet is routed from  $PN_{1S}$  to  $PN_{2L}$ , these durations are marked as HFPT  $PN_{1L}$  and HFPT  $PN_{2L}$ , respectively. The HF channel is available for data transferred during the time intervals  $t_1-t_2$  and  $t_3-t_4$ , and these durations are marked as HFDT. Additionally,  $\alpha_1$  and  $\alpha_2$  are the time-allocation values requested by the load and determine the size of the HF power packet generated by the power transmitter node. Since,  $T_W$  is the total time required for completing a full HF power and data transfer cycle for the designed SIMO HFDPS, it also represents the switching cycle time for all the power nodes in which they need to achieve their inductor charge balance and capacitor voltage balance for ensuring a stable steady-state operation.

An illustrative experimental setup for the SIMO realization is captured in Fig. 7(c) along with experimental results in Fig. 7(d) and (e). These results are obtained with each load node terminating in separate passive load. In contrast, Fig. 8 shows the output waveform when the two outputs in Fig. 7(a) are connected in a differential-mode configuration with an ac passive load and each load node receiving sinusoidally coded energy packets yielding a familiar sinusoidal (inverter) ac output voltage and current [13] with the exception that routing eliminates about 25% of the power-stage hardware in [13].

#### IV. CONCLUSION

In this brief letter, the utility of coding energy transfer, if done appropriately, has been illustrated using some novel innovations. Essentially, the technologies outlined have the potential

to enable controlled intermediate digitized/discretized energy transfer and go beyond continuous power transfer, thereby yielding advantages including but not limited to energy transfer efficiency, packetized energy controllability to name a few. Extending the concept from SISO to SIMO/MIMO will require further work not limited to stability, controllability, routing [8], and waveguide, thereby providing further exciting possibilities. With regard to the first two issues, the fundamental work based on multiscale modeling and stability of the author, as captured in [11] and [12], is an initial step in which direction can assess stability and controllability in terms of the evolution of the switching states (i.e., switching sequences) of the power-conversion system and application load. Other small-signal approaches can also be found in the literature, such as those captured in [13].

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