DLI BASED TDM-MIMO CONVERTER FOR MULTIPLE OUTPUT CHARGER

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ABSTRACT: Multiple-input multiple-output (MIMO) converters have been identified as a cost-effective approach for energy harvesting and dispatching in hybrid power systems such as those envisioned in future smart homes and DC microgrids. Compared with relatively complex set-up of single-input single-output (SISO) converters linked at a common DC bus to exchange power, the MIMO converters possess promising features of fewer components, higher power density, and centralized control. This thesis addresses various issues regarding the development of MIMO converters. Both non-isolated and isolated MIMO converter topologies are proposed. Steady-state analysis and dynamic modeling of MIMO non-inverting buck–boost and flyback converters are introduced and presented in detail. Specific switching strategies are proposed and appropriate control algorithms are presented to enable power budgeting between diverse sources and loads in addition to regulating output voltages. Furthermore, a simple method is put forward for deriving the non-isolated MIMO converters with DC-link inductor (DLI) and DC-link capacitor (DLC). Based on a basic structure, a set of rules is listed for the synthesis of MIMO converters. Using the time-sharing concept, multiple sources provide energy in one period, and multiple loads draw energy in the subsequent period. In the end, general techniques are introduced for extending the SISO converters to their MIMO versions, where parts of the conventional SISO converters are replaced with multiport structures.

INTRODUCTION

Utilization of renewable energy sources on user premises has attracted a significant interest for many commercial and industrial applications owing to their merits of non-pollution and rich reserves. Due to the intermittent nature of renewable energy, storage and standby sources are usually required to function as backup. A hybrid power system may lower environmental impacts and improve security of supply. Besides, a simultaneous combination of sources is available for optimal energy/economic dispatch. At the same time, many loads and appliances used in offices, commercial facilities, and residential buildings often dictate the need of power supply with different gains. Thus, the need of technology for distributing power to a variety of consumption loads whose voltage levels are different motivates the development of supply structure with multiple voltages.

Many distributed energy resources include but are not limited to solar panels and fuel cells generate DC voltages, and a growing number of consumption loads and appliances are using DC, e.g. data centers, portable devices, LED lights, etc. Thus, DC distribution systems are envisioned to interact with different energy sources, modern electronic loads and storage units for simplicity and efficiency [1]–[3]. Figure 1.1 shows a conceptual DC power distribution architecture for future residential applications where wind and solar energy are interfaced, storage devices are installed, and different loads are powered. Usually, there are two approaches to form such a system with multiple ports. Conventionally, single-input single-output (SISO) converters are arranged in parallel at a common DC bus to exchange power (Figure 1.2). In this architecture, separate conversion stages are employed for individual sources and loads, and the converters would be controlled independently. Thus, a communication system may be included to exchange information and manage the power flow between different ports. Although such a configuration is prevalent in distribution systems today, complex configurations generally result in a large number of modules and high costs. In addition, the communication-based control system may cause software delays and data errors, which would also degrade the performance of the system [4]. As

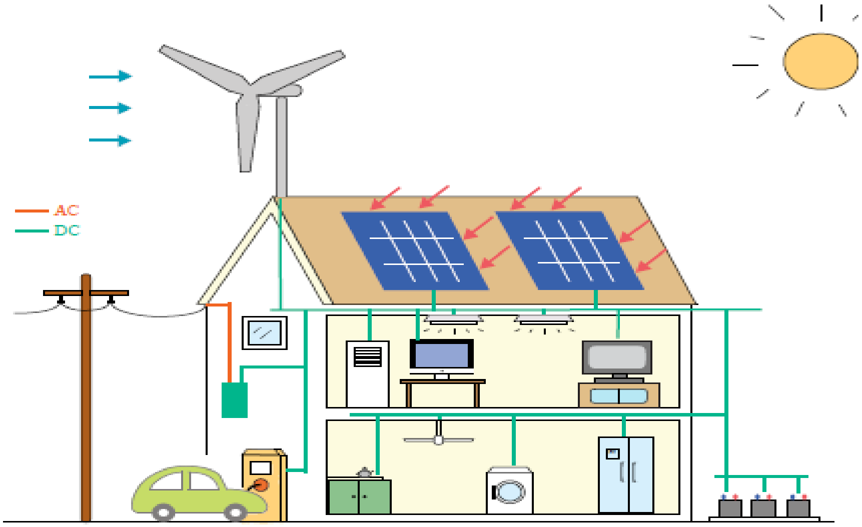

Figure 1.1. Example of residential low-voltage DC power distribution system.

a prominent alternative, multiple-input multiple-output (MIMO) converter can replace the complicated set-up, as pictured in Figure 1.3. In this integrated and single-stage conversion architecture, voltage regulation and power management can be carried out simultaneously. Additionally, compact packaging and relatively straightforward control become possible.

Though less attention has been given to the development of MIMO converters so far [5]–[8], multiple-input single-output (MISO) converters and single-input multiple-output (SIMO) converters have been well studied. In the established literature, MISO converters are identified as a cost-effective and modular technology to incorporate more than one source. Applications of using MISO converters for integrating sources with complementary nature have been found in photovoltaic-utility systems [9]–[12], photovoltaic-wind systems [13]–[16], renewable generation systems with battery backup [17]–[22], and hybrid electric vehicles [23]–[30]. Meanwhile, SIMO converters are seen as an efficient power router to feed several loads. Many SIMO converters have been reported in the literature for various applications, such as portable and electronic devices [31]–[38], telecom and computer systems [39]–[41], fuel cell generation systems [42], diode-clamped multilevel inverters [43]–[45], and others [46], [47].

The motivation of this thesis is to design MIMO converters, which can combine the advantages of MISO and SIMO converters. The proposed MIMO converters can be a substitute of the conventional architecture consisting of SISO converters to simplify the conversion structure and provide easy energy management. The reduced conversion stage may also improve the power density and eliminate complicated conventional communication-based control issues between individual conversion stages. With proper design, flexibility of source integration and power dispatching may be enhanced for the distribution systems, while savings in manufacturing cost and mass become achievable. Although the MIMO converter topologies discussed in this thesis may only allow for unidirectional inputs, bidirectional power flow can be done extrinsically by using additional converters

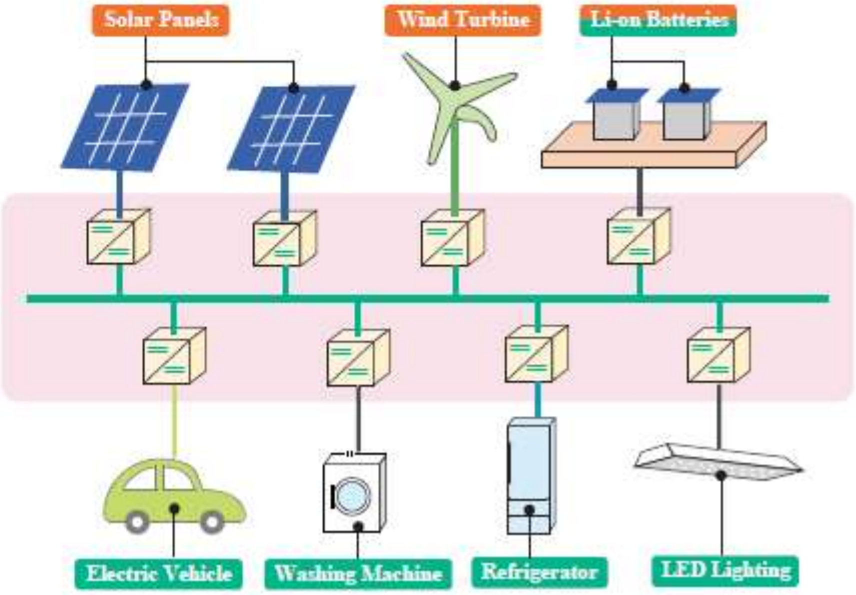

Figure 1.2. Conventional DC distribution system with multiple SISO converters.

LITERATURE REVIEW

In general, the multiport converters, including MISO, SIMO, and MIMO converters, can be classified into two categories: non-isolated topologies and isolated topologies. The non-isolated topologies possess advantages of compact structure, low cost, high power density and straightforward power flow control. A drawback of this kind of structure lies in the fact that a wild range of voltage transformation is not easily obtainable and galvanic isolation is not provided (even when it may be a requirement). Non-isolated MISO converters can be derived from a single converter, i.e. buck [48], boost [49], buck–boost [50]–[52], Ćuk [53] and SEPIC [54], [55], or a combination of several converters, such as buck/buck–boost [15], buck/SEPIC

Isolated topologies include a transformer and adjustment of voltage levels through changing the transformer turns ratio could be beneficial to avoid the device handling high voltage and current. However, complex circuitry and control strategy may mitigate the converters' performance. Isolated MISO converters can be derived from flyback [9], [10], and bridge [58]–converters. Isolated SIMO converters may be generated from flyback [31], [32], [63], forward [39], push-pull [64], and bridge [40] topologies. Moreover, derivations of isolated SIMO converters can be based on a combination of flyback and forward converters [65], [66].

MISO Converters

Multiple input sub-circuits can be placed in parallel or series. In parallel configurations, MISO converters can be obtained by adding primary windings and primary side sub-circuits of a conventional flyback converter [9], [10], or paralleling the input sub-circuits of a buck–boost converter [12], [50]. As these converters are designed in a time shared operation mode, only one source is allowed to deliver power at a time. This limitation can be overcome by using current-source converters. For example, [58] presented a full-bridge isolated boost converter, but the number of required switches is four times the input ports. Reference [67] proposed a half-bridge isolate boost topology. Though the number of switches is reduced by half, the need of inductors is doubled. Therefore, it still makes the design inherently complex and costly. Other alternatives include connecting the multiple input sub-circuits at trivial points, such as linking the SISO converters by paralleling them at the output capacitor [24], [26]. Moreover, connection of multiple input sub-circuits may occur in a series way [13], [14] to achieve simultaneous power transfer. The authors of [68] and [69] also proposed a method in which the MISO converters are accomplished by means of series-connected H-bridge cells.

SIMO Converters

SIMO converters can be obtained by placing sub-circuits in parallel or series at the output side. In parallel configurations, a straightforward method to provide multiple outputs is to use a transformer with multiple secondary windings. Based on this approach, two topologies are commonly used due to simplicity and effectiveness, i.e. SIMO flyback and forward converters. The SISO flyback converter topologies have fewer components, but face a cross-regulation problem [70]. In order to keep all the output voltages tightly regulated, various approaches have been proposed [71], [72]. Likely, SIMO forward converters also have a drawback of poor regulation, and several methods are readily taken to improve the converters' performance [73]Instead of using a transformer, the authors of [34] came up with a method to realize a controlled current source and distribute the current to the outputs on an interleaving basis. Authors of [57] introduced a class of topologies where only one inductor was implemented while several outputs were regulated. The inductor is sequentially connected in a parallel output arrangement with a number of loads via a switch-network. Some of the proposed topologies are also capable of producing bipolar output voltages. In series configurations, the authors of [44] and presented a SIMO converter topology for applications in feeding multilevel inverters.

MODELLING

The schematic diagram of the proposed MIMO non-inverting buck–boost converter is depicted in Figure 2.1. The input voltages are $V_{in,i}$ (i = 1,…, m) and the output voltages are $V_{out,\ j}$ (j = 1,…, n). All the input switches $S_{in,i}$ (i = 1,…, m) are bidirectional-carrying forward-blocking, and all the output switches $S_{out,\ j}$ (j = 2,…, n) are forward-conducting bidirectional-blocking, except for $S_{out,1}$. The bidirectional-carrying forward-blocking switch is realized by a MOSFET, and the forward-conducting bidirectional-blocking switch is realized by a series MOSFET and diode pair. The inputs can be arbitrarily ordered. For simplicity of analysis, the inputs are arranged in an descending order of duty ratios; that is $D_{in,1} > D_{in,2} > \cdots > D_{in,m}$. The outputs are assumed to be regulated such that $V_{out,1} > V_{out,2} > \cdots > V_{out,n}$. All the MOSFETs operate at the same switching frequency, and the gating signals are depicted in Figure 2.2. The trailing edges of the input and output MOSFETs' gating signals are synchronized, respectively. Switch S is on whenever any input switch $S_{in,i}$ (i = 1,…, or m) is on. It is off only when all the input switches are off.

The concept of the overlapping duty ratio $D_{in,\ olp,\ i}$ (i = 1,…, or m) of the input switch is defined as the portion of time when there are i inputs supplying power at a time

$$D_{in,olp,i} = \begin{cases} D_{in,i} - D_{in,i+1}, & i = 1,\ldots,m-1 \\ D_{in,i}, & i = m. \end{cases}$$

If two or more output switches conduct at a time, only the one connected to the lowest-voltage output is on, and the others are off. The concept of the effective duty ratio $D_{out,eff\ ,\ j}$ (j = 1,…, or n) of the output switch is defined as the portion of time when the jth output switch $S_{out,\ j}$ carries nonzero current

Operational Analysis of the Circuit

The basic principle of the MIMO non-inverting buck–boost converter is to charge the inductor L from $V_{in,i}$ (i = 1,…, or m) or their combination in one period, and discharge it to the output capacitors C_j and loads R_j (j = 1,…, n) in the subsequent period of a switching cycle T_s. Thus, the converter exhibits two operating stages depending on the state of the inductor (refer to Figure 2.3).

Stage 1: The inductor is in charge-state. Switch S is on, at least one input switch $S_{in,i}$ (i = 1,…, or m) is on, and all the output switches $S_{out,\ j}$ (j = 1,…, n) are off. The inductor L is energized, and power demands for the loads R_j (j = 1,…, n) are satisfied by discharging the output capacitors C_j (j = 1,…, n). There are m subintervals in this stage. If k input switches $S_{in,i}$ (i = 1,…, k) are on, power is delivered from the k inputs $V_{in,i}$ (i = 1,…, k) simultaneously, and the inductor voltage V_L is $V_{in,1} + V_{in,2} + \cdots + V_{in,k}$

Stage 2: The inductor is in discharge-state. Switch S is off, and all the input switches $S_{in,\ i}$ (i = 1,…, m) are off. The inductor L is discharged. If several output switches are on at a time, the inductor voltage is equal to the lowest of the output voltages for which respective switch is on. In this stage, there are n subintervals. The energy storage in inductor L is released to the output capacitors C_j and loads R_j (j = 1,…, n) in a sequential manner.

In the following derivations, the converter is assumed to be lossless. The lower-case variables represent the large-signal states, upper-case variables represent the equilibrium points, and the hatted variables denote the small-signal perturbations. Both continuous conduction mode (CCM) and discontinuous conduction mode (DCM) are analyzed.

DCM

If the inductor current collapses to zero in its pth discharge subinterval (refer to Figure 2.4), the MIMO converter is defined to operate in the pth discontinuous mode. Similar to CCM, the inductor current is assumed to change linearly in each subinterval. Since the inductor current starts from zero each switching cycle in DCM, the peak inductor current and the energy stored in the inductor at the very beginning when the inductor gets discharged is $0.5LI^2_{L,\ peak}$

DESIGN OF DLI-Coupled MIMO Converters

As the average current of the inductor shall not depend on the connected PSCs or FCs, DLI is used to link the multiple PVSCs and multiple C-FCs. The synthesis of the DLI-coupled MIMO converters is briefly described as follows:

Step 1: Choose appropriate PVSCs and combine them according to the connection rules.

Step 2: Construct the multiple-output structure by combining the C-FCs based on the connection rules.

Step 3: Link the multiple PVSCs and multiple C-FCs with DLI.

Figure shows six DLI-coupled MIMO converter topologies generated by using buck PVSCs and C-FCs. The subfigures in the first and second columns show topologies synthesized by series-connected and parallel-connected multiple buck PVSCs, respectively. In series input configurations, as the freewheeling diodes associated with the DLI is redundant, it can be removed. Also, the PVSCs can supply power to the DLI either individually or simultaneously. In parallel input configurations, a diode is inserted in series with MOSFET of each PVSC to avoid direct parallel connection.

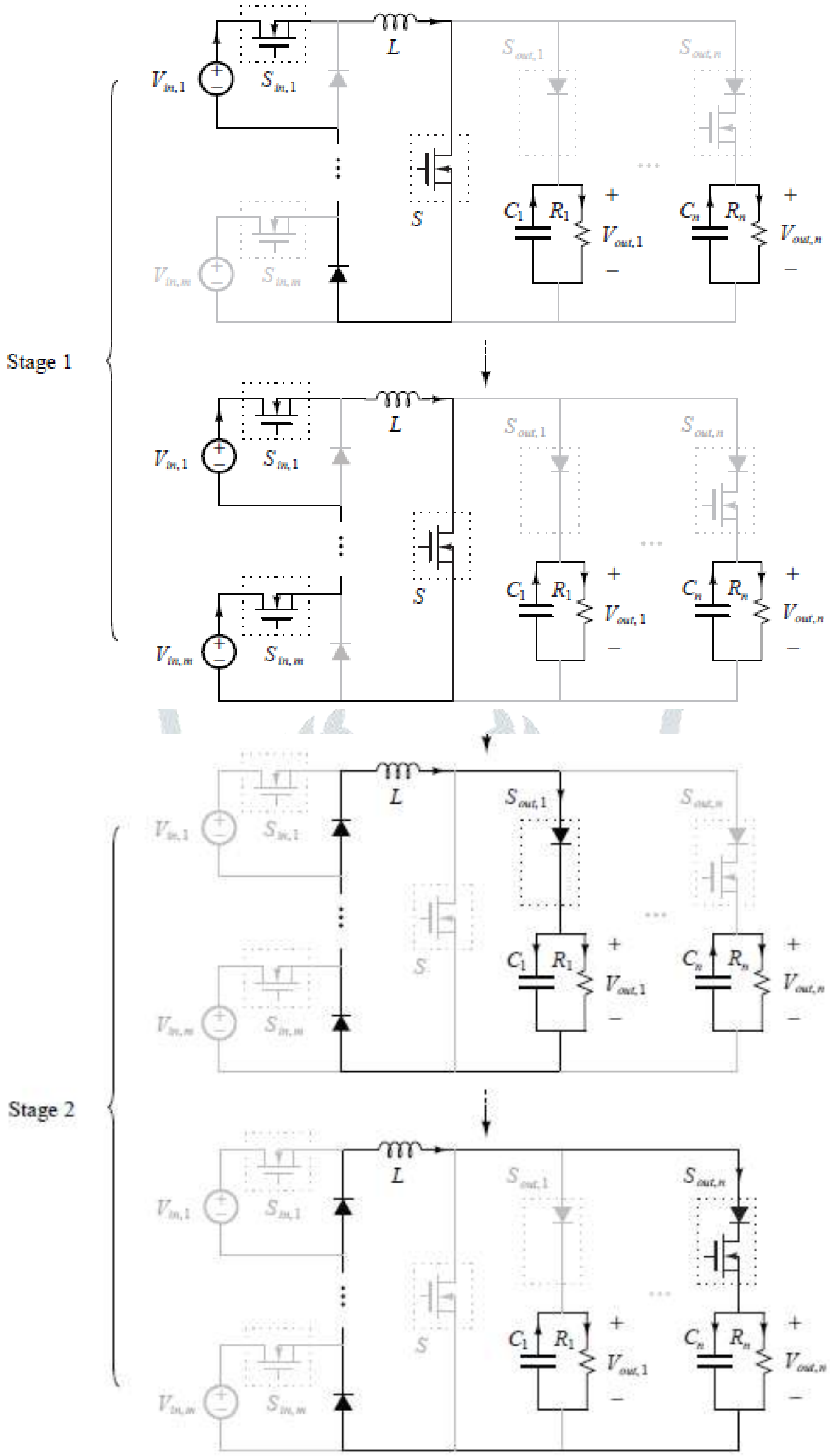

Figure 2.3. Two operating stages of MIMO non-inverting buck–boost converter.

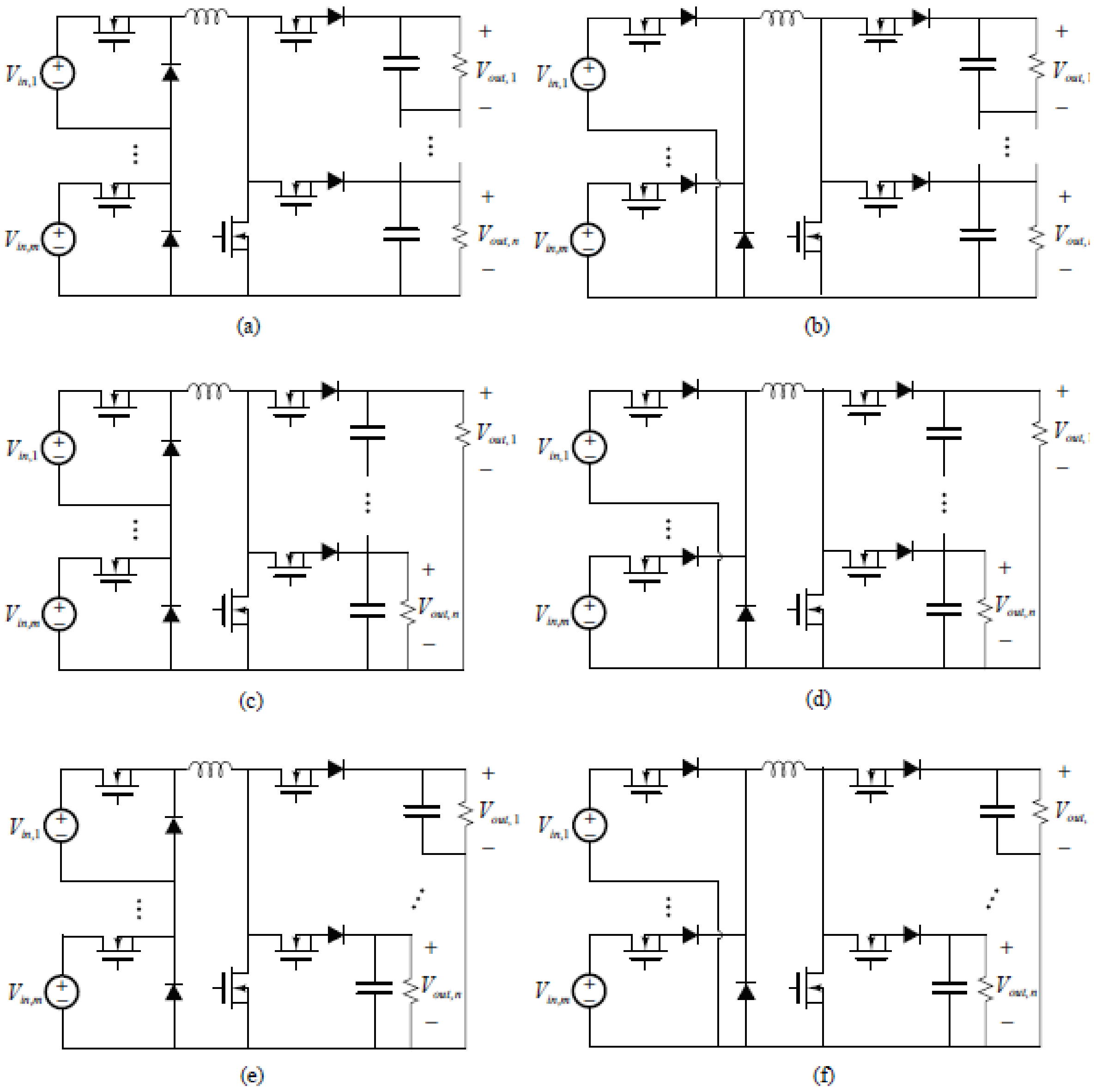

Figure Buck-derived DLI-coupled MIMO Converters: (a) buck PVSCs in series and C-FCs in series with series outputs; (b) buck PVSCs in parallel and C-FCs in series with series outputs; (c) buck PVSCs in series and C-FCs in series with parallel outputs; (d) buck PVSCs in parallel and C-FCs in series with parallel outputs; (e) buck PVSCs in series and C-FCs in parallel with parallel outputs; and (f) buck PVSCs in parallel and C-FCs in parallel with parallel outputs.

As the average voltage of the capacitor shall not depend on the connected PSCs or FCs, DLC is used to link the multiple PCSCs and multiple LC-FCs. The synthesis of DLC-coupled MIMO converters is described as follows:

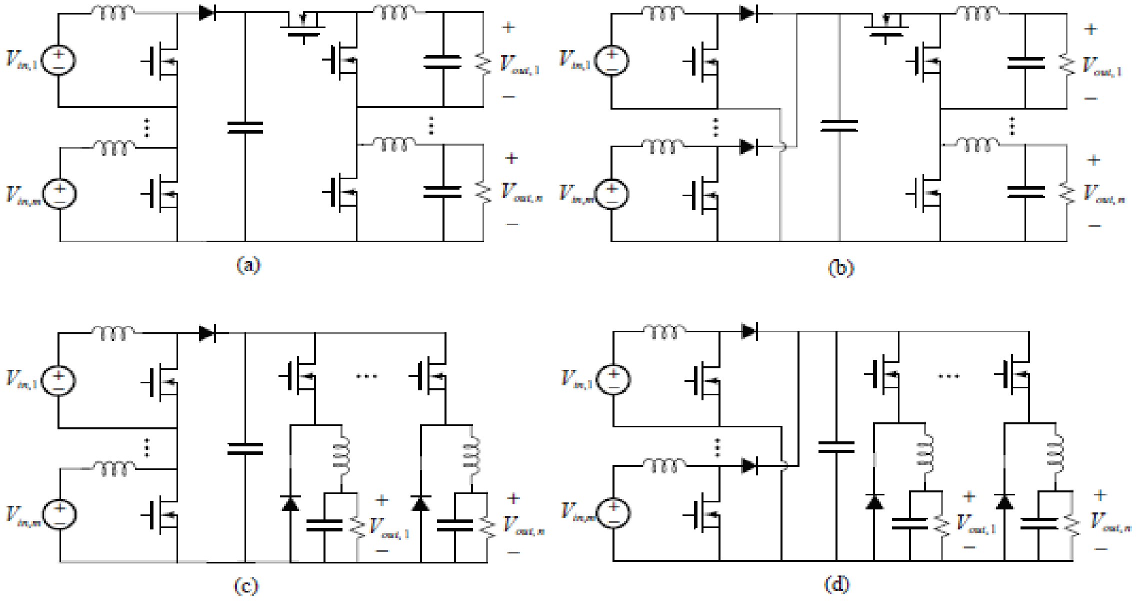

Figure Boost-derived DLC-coupled MIMO Converters: (a) boost PCSCs in series and LCFCs in series; (b) boost PCSCs in parallel and LC-FCs in series; (c) boost PCSCs in series and LC-FCs in parallel; and (d) boost PCSCs in parallel and C-FCs in parallel.

Step 1: Choose appropriate PCSCs and combine them according to the connection rules.
Step 2: Construct the multiple-output structure by combining the LC-FCs based on the connection rules.
Step 3: Link the multiple PCSCs and multiple LC-FCs with DLC.

Following the synthesis procedure, four DLC-coupled MIMO converter topologies are generated by using boost PCSCs and LC-FCs, as shown in Figure . The subfigures in the first and second columns of Figure show topologies synthesized by series-connected and parallel connected multiple boost PCSCs, respectively. In series input configurations, the MOSFET of each PCSC also provides a freewheeling path for other PCSCs when it does not supply power externally. In this case, only one PCSC is allowed to supply power to the DLC at a time. In parallel input configurations, the diode associated with the DLC is removed due to redundancy.

Also, power can be supplied simultaneously from the PCSCs. The subfigures in the first and second rows of Figure depict MIMO converters with series-connected multiple LC-FCs and loads, and parallel-connected multiple LC-FCs and loads, respectively. In the series output configurations, only one load is allowed to draw power from the DLC through the LC-FC because series connection of current sources should be avoided. In parallel output configurations, the loads can draw power through the LC-FCs either individually or simultaneously.

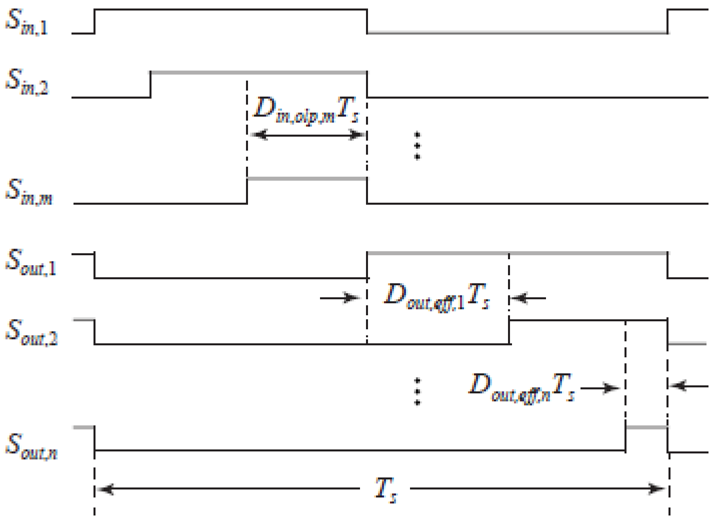

Figure Switching pattern for the Zeta-derived DLI-coupled MIMO converter.

RESULTS

A double-input double-output Zeta-derived DLI-coupled converter is considered in this section. Two input voltages $V_{in,1}$ = 120 V and $V_{in,2}$ = 50 V are assumed. The outputs are regulated at $V_{out,1}$ = 48 V and $V_{out,2}$ = 24 V, while two 1 Ω resistors define the loads. $P_{in,2}$ is kept at 1.5 *k*W while $P_{in,1}$ is relaxed. To demonstrate the operation of the proposed MIMO converter, several transient studies are described below, in which the converter is assumed to initially operate in steady state defined by the nominal condition specified above.

In the first study, a step-change in $V_{in,2}$ from 50 V to 60 V is applied. The converter response is depicted in Figure 4.19, which indicates the output voltages are regulated and return to their desired values after the transient. Since the demanded power stays the same, the input powers drained from both sources return to their preset values.

In the second study, the converter response to a load change is considered. Figure 4.20 shows the system response to the first load R_1 changing from 1 Ω to 0.7 Ω. The controller regulates the outputs to track the specified voltage values, while the increased power demand from R_1 is compensated by the first input. The input power $P_{in,2}$ is regulated to remain constant at the reference level of 1.5 *k*W.

In the final study, it is assumed that the second source $V_{in,2}$ is disconnected. Figure 4.21 illustrates the simulation result corresponding to this event. The power drop in the second input automatically results in the first input supplying the deficit power. The output voltages undergo a transient and return to their specified reference levels, as expected.

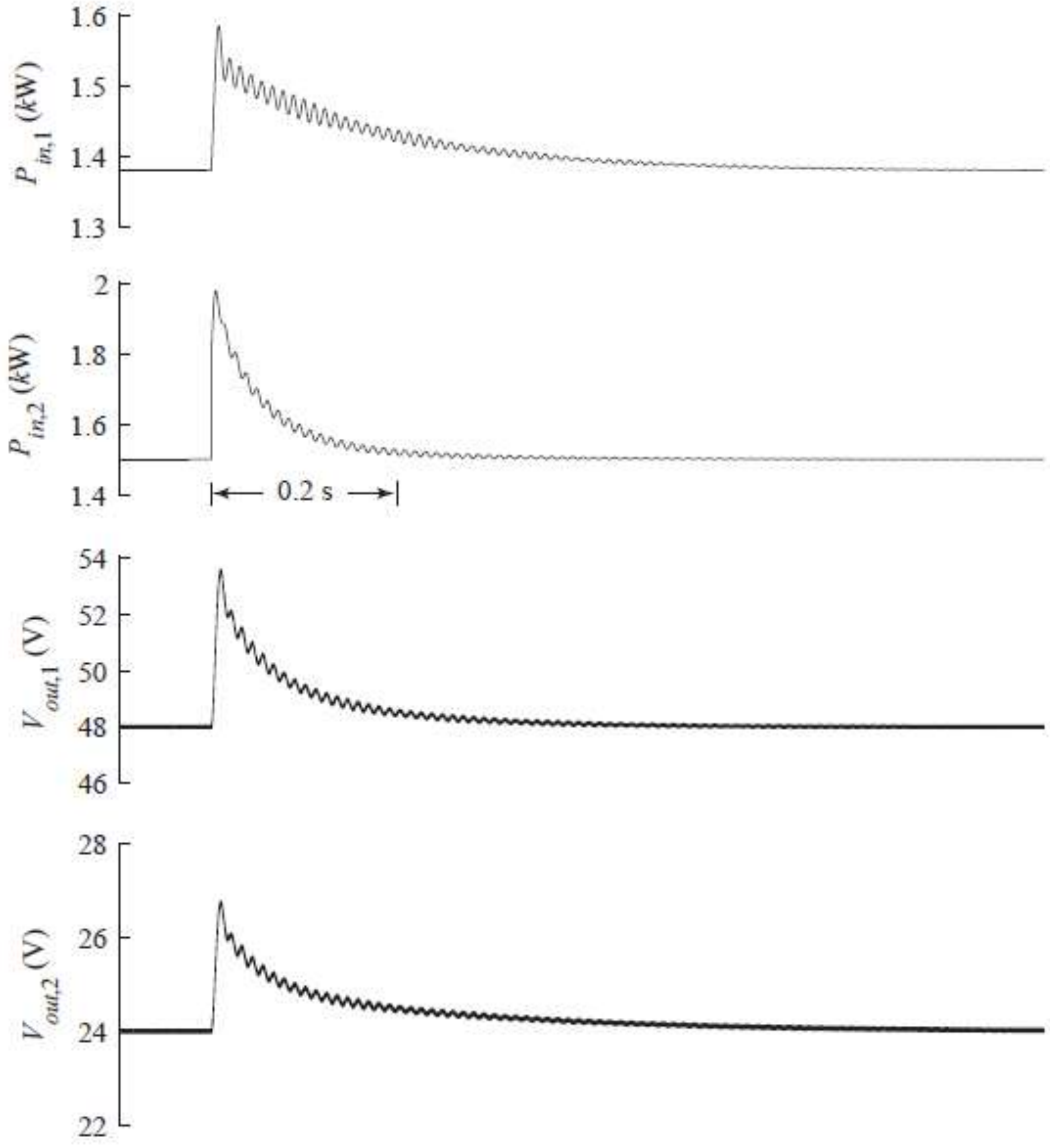

Figure Simulated waveforms of the Zeta-derived DLI-coupled MIMO converter in response to step change in input voltage.

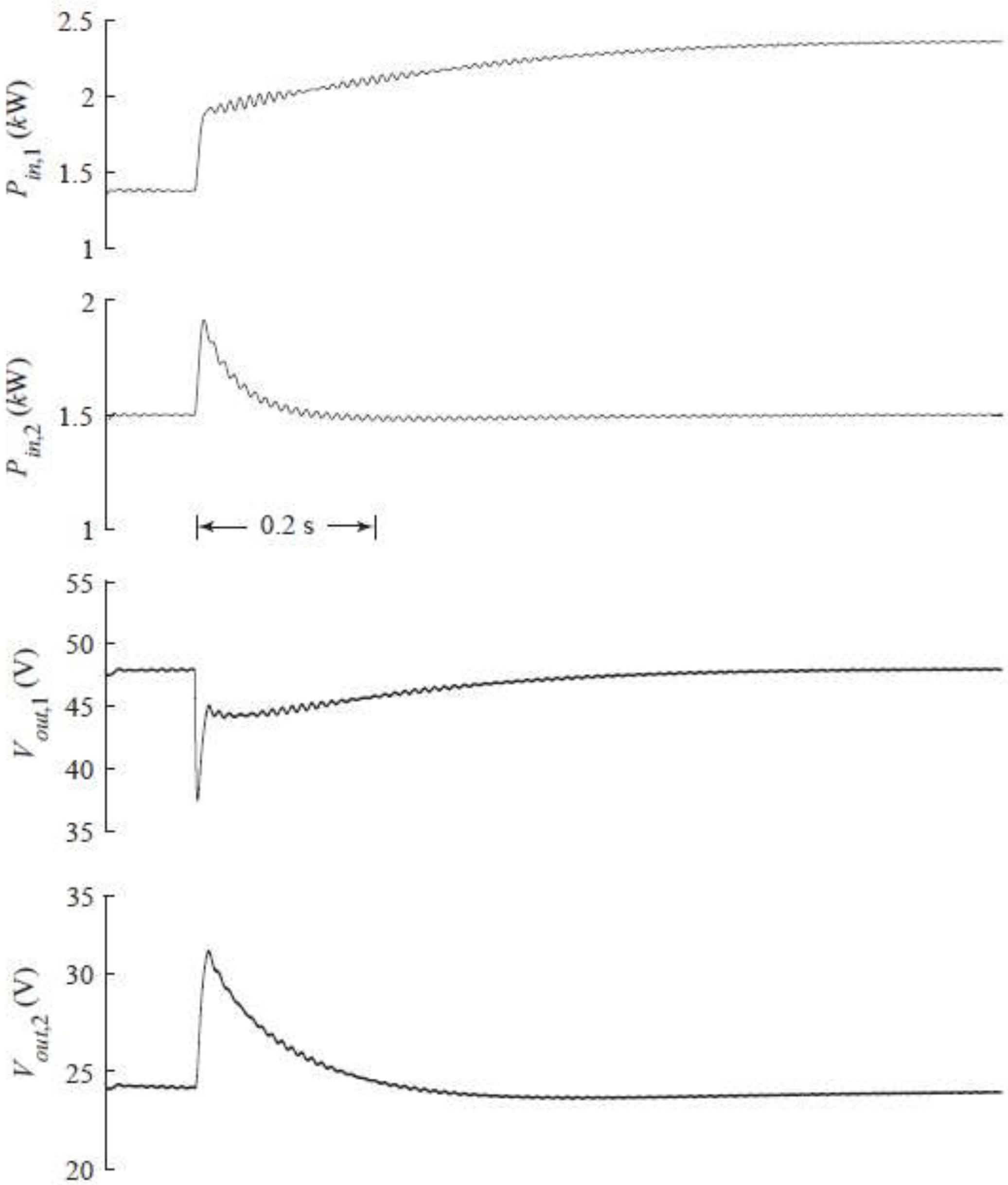

Figure: Simulated waveforms of the Zeta-derived DLI-coupled MIMO converter in response to step change in load.

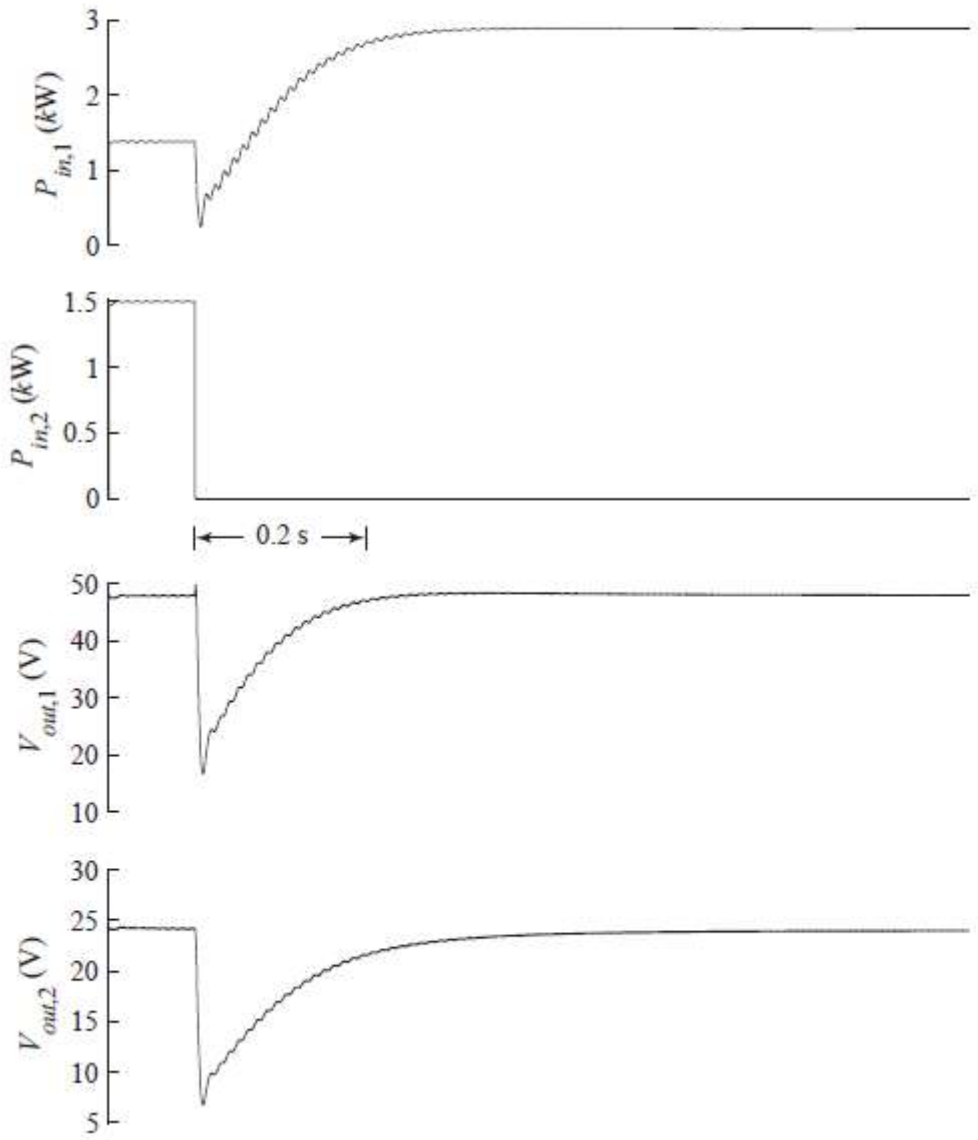

Figure Simulated waveforms of the Zeta-derived DLI-coupled MIMO converter in response to one source missing.

CONCLUSION & FUTURE SCOPE

With basic building blocks (including PSCs and FCs), a basic structure based on DLI/DLC is proposed for the synthesis of a family of non-isolated MIMO converters. Connection rules for building blocks of PSCs and FCs are listed. Formalization of interface between multiple PSCs and FCs is realized by DLI or DLC with necessary switches. Following a uniform method, two types of DC-linked MIMO converters are obtained. In the end, a set of uniform rules for synthesizing general MIMO converters based on basic SISO converters are proposed. MIMO converters can be derived by replacing the PSC or original DC source of a conventional converter with series- or parallel-connected PSCs, and the FC or original DC load with series- or parallel-connected FCs. However, to satisfy the application where an energy storage element is indispensable, bidirectional power flow is required. Instead of using additional converter for feeding the energy back, it would be desirable to analyze and synthesize bidirectional multiport converters.

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