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Interleaved switched tank converter with coupled inductors

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ABSTRACT

This disclosure describes modular, low-cost, high-efficiency, high power-density techniques to convert electrical power in a 2n:1 (n ≥ 2) ratio, e.g., 4:1, 6:1, 8:1, etc. The techniques are robust to component non-idealities over a wide range of operating conditions, and minimize current stress on components. The disclosed interleaved structure cancels input current ripple and thereby reduces the need for input-filtering capacitors. The switched tank converters find application in data centers, where DC-DC conversion is frequently required, e.g., from a bus voltage of forty-eight volts to an intermediate bus voltage of twelve or six volts.

KEYWORDS

- Voltage conversion
- Switched tank converter
- DC-DC power converter
- LC resonant tank
- Data center power

BACKGROUND

Recent disclosures [1], [2] have described switched tank converters (STC) for non-isolated DC-DC conversion. As opposed to switched capacitor converters, these STCs use coupled inductor to partially replace flying capacitors for the purposes of energy transfer. The STCs thereby achieve soft charging, soft switching, and minimal device voltage stresses under most operating conditions. The number of components required by such STC converters can be high, e.g., up to ten switches and an equivalent number of capacitors. Besides, the design of the current STC converters do not extend immediately, e.g., modularly, to larger power conversion ratios, e.g., 8:1.

DESCRIPTION

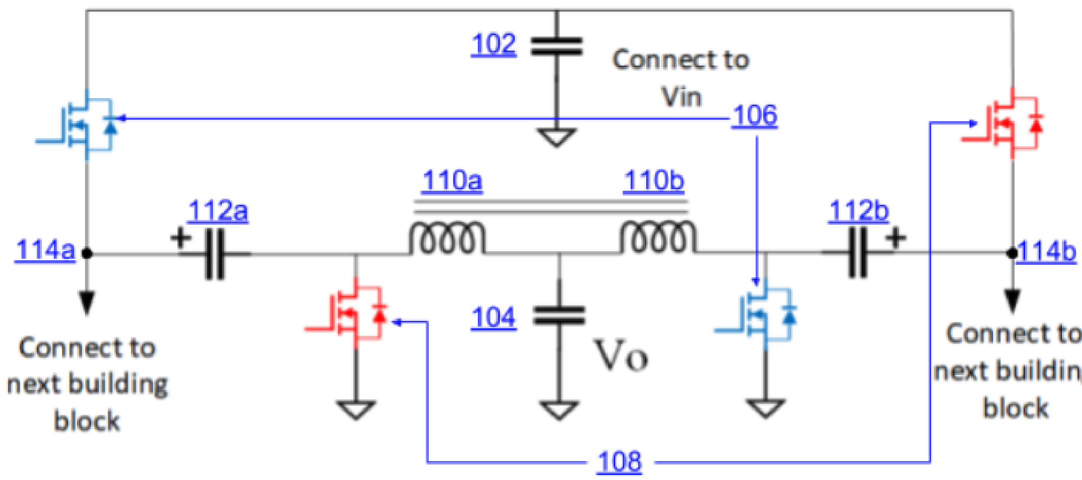

Fig. 1: The building block

Fig. 1 illustrates a modular circuit that can be used as a building block to construct DC-DC power converters of various input-to-output voltage ratios, per techniques of this disclosure. The input (Vin) is connected across capacitor 102, and the output voltage (Vo) appears across capacitor 104. The circuit has a single input and a single output. The output capacitor 104 is tied to the output voltage Vo. The blue switches (106) are each in phase with each other, and the red switches (108) are each in phase with each other. The blue switches and the red switches each have a non-overlapping 50% duty cycle. Electromagnetically coupled inductors (110a-b) connect flying capacitors (112a-b) to their outputs. As shown, points 114a-b of the building block are connected to the next building block in order to build circuits of various voltage conversion ratios. For example, two connected building blocks achieve a 4:1 voltage conversion ratio; three connected building blocks achieve a 6:1 voltage conversion ratio; etc. In the last building block of a connected cascade of building blocks, the capacitors 112a-b on the lower leg of the building block are shorted.

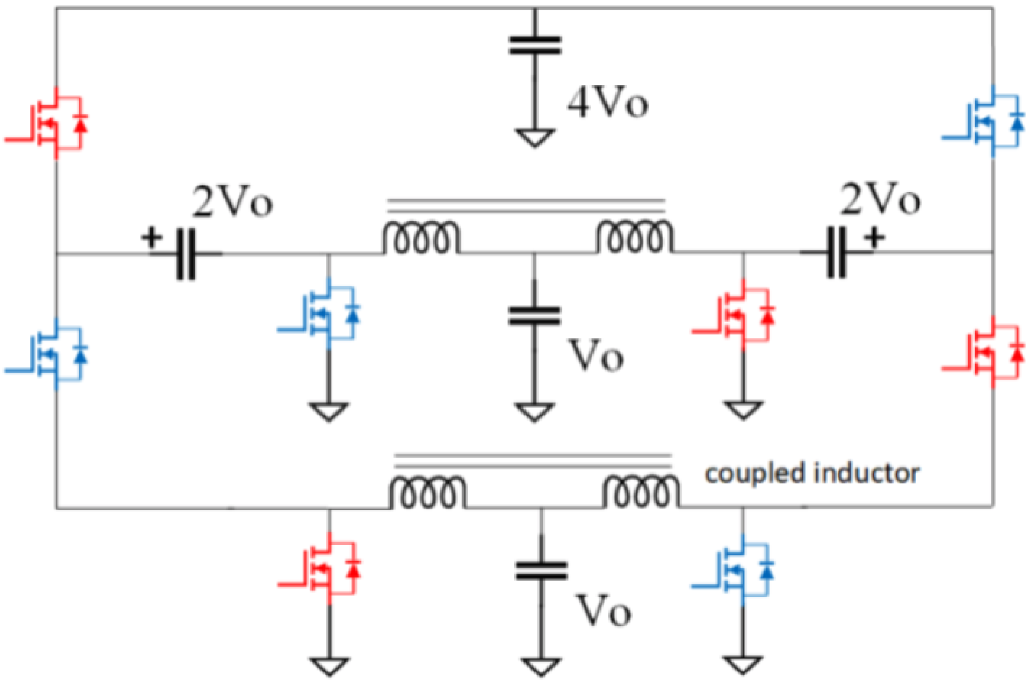

Fig. 2: A 4:1 DC-DC converter

A DC-DC converter with a voltage conversion ratio of 4:1, built with two building blocks, is illustrated in Fig. 2. As mentioned earlier, the capacitors on the lower leg of the last building block are shorted. The circuit of Fig. 2 has a single input and a single output. The output capacitor is tied to the output voltage Vo. The input voltage (4Vo) is four times the output voltage.

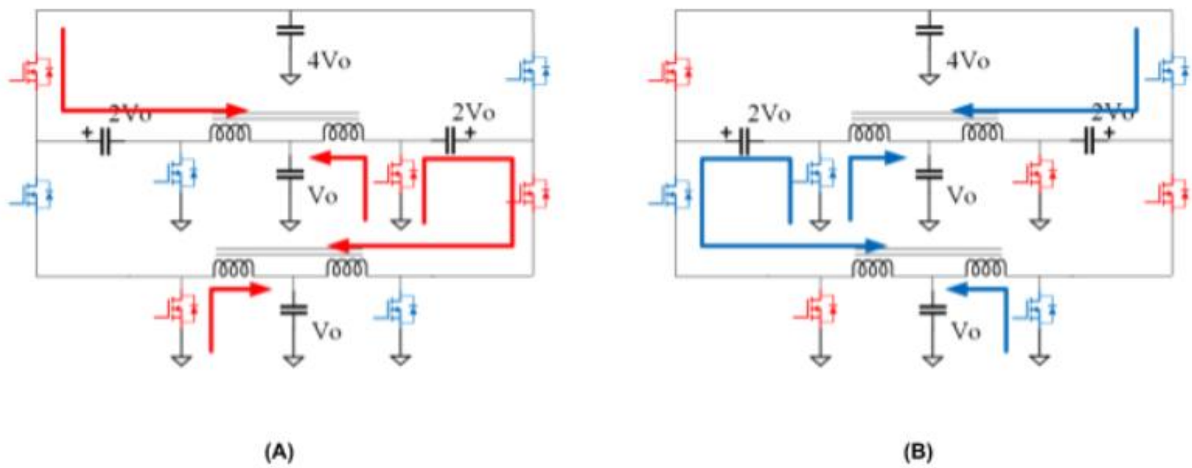

Fig. 3: Operating stages of a 4:1 DC-DC converter (A) Stage-1 - the red switches are closed and the blue switches are open (B) Stage-2 - the red switches are open and the blue switches are closed.

Fig. 3 illustrates the operating stages of a 4:1 DC-DC converter. In stage-1 (Fig. 3A), the red switches conduct current while the blue switches are open. The red arrows indicate the direction of current flow. In stage-2 (Fig. 3B), the blue switches conduct current while the red switches are open. The blue arrows indicate the direction of current flow. In stage-1, the left-side flying capacitor is charged by the input voltage, while a lead of the lower left-side inductor is tied to ground, so that a 4:1 input-to-output voltage conversion ratio is achieved. In stage-2, the right-side flying capacitor is charged by the input voltage, while a lead of the lower right-side inductor is tied to ground, so that a 4:1 input-to-output voltage conversion ratio is again achieved. Stages 1 and 2 alternate in time to produce a 4:1 DC-DC voltage conversion through all time.

As is seen from Fig. 3, the coupled inductor windings conduct current at both stages, thereby reducing the current stress on switches and inductors, and achieving high efficiencies and power densities. The left and right halves of the circuit are active in opposite phases. This left-right interleaved structure balances load and enables input current to flow at both operating stages, thereby reducing current ripple and reducing or obviating the need for input filtering capacitors.

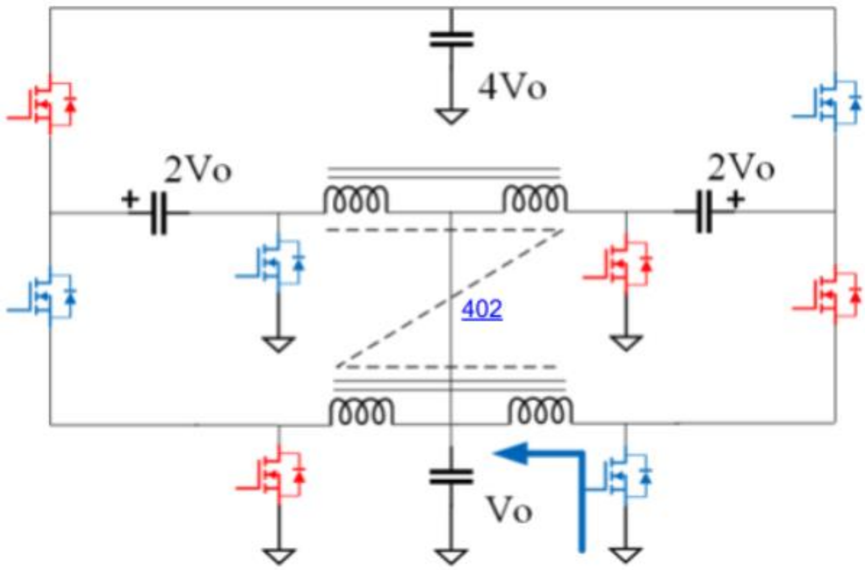

Fig. 4: A 4:1 DC-DC converter of interleaved STC design, with a four-winding coupled inductor

Fig. 4 illustrates an alternate implementation of a 4:1 DC-DC converter in which a four-winding coupled inductor (402) is used in place of a pair of two-winding coupled inductors. The dotted-Z pattern shows the inductors that are electromagnetically coupled.

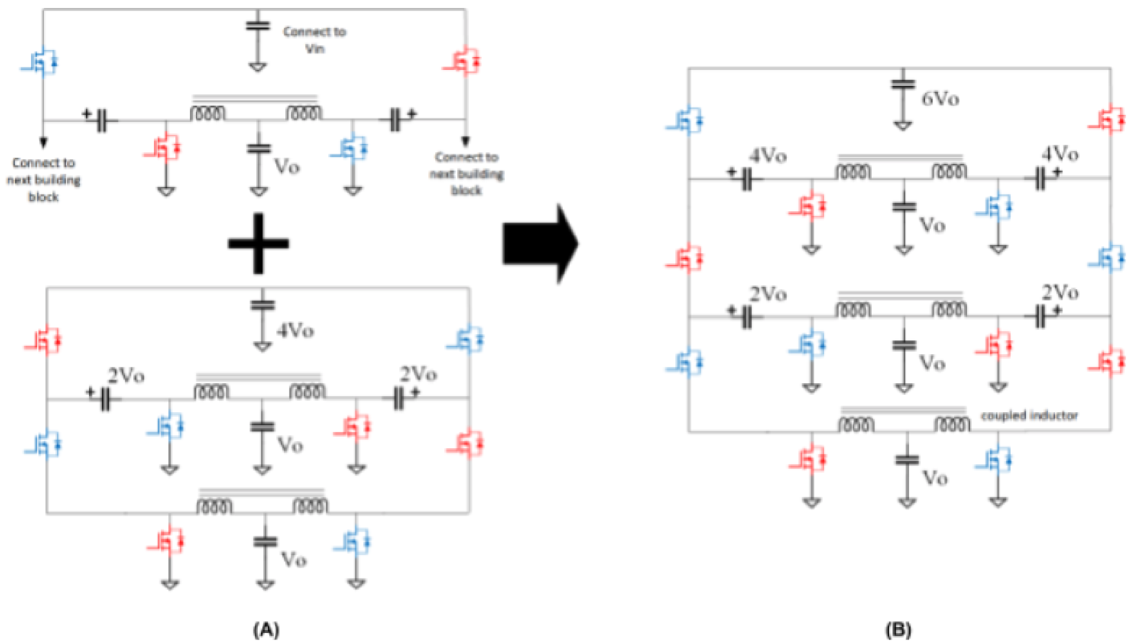

Fig. 5: A 6:1 DC-DC converter (A) Construction from modular building blocks (B) A 6:1 DC-DC converter

Fig. 5B illustrates a 6:1 DC-DC converter, which is constructed from the union of the modular building block and a 4:1 DC-DC converter, as shown in Fig. 5A.

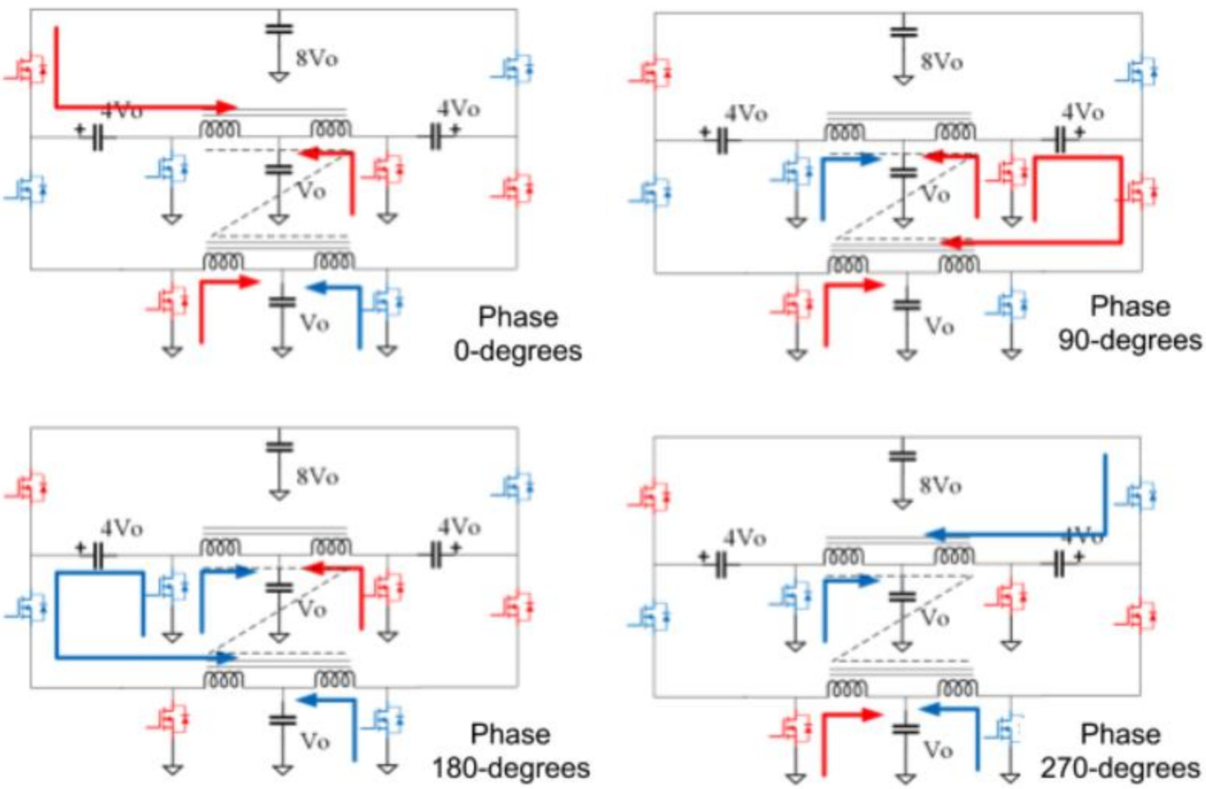

Fig. 6: Operating stages of an 8:1 DC-DC converter constructed with a topology similar to that of a 4:1 DC-DC converter

Fig. 6 illustrates an 8:1 DC-DC converter with circuit topology similar to the 4:1 DC-DC converter of Fig. 4, where the higher voltage conversion ratio is obtained by modifying the duty cycles of constituent switches away from 50%. The circuit of Fig. 6 operates in four operating stages, e.g., phase 0-degrees, phase 90-degrees, phase 180-degrees, and phase 270-degrees. The four floating FET switches each have a 25% duty cycle, and the four ground-connected FET switches each have a 75% duty cycle. As shown, a four-phase coupled inductor (indicated by dotted-Z) is used in this circuit. The component count of this 8:1 converter is almost the same as the component count of the 4:1 converter.

CONCLUSION

This disclosure describes modular, low-cost, high-efficiency, high power-density techniques to convert electrical power in a 2n:1 ($n \geq 2$) ratio, e.g., 4:1, 6:1, 8:1, etc. The techniques are robust to component non-idealities over a wide range of operating conditions, and minimize current stress on components. The disclosed interleaved structure cancels input current ripple and thereby reduces the need for input-filtering capacitors. The switched tank converters find application in data centers, where DC-DC conversion is frequently required, e.g., from a bus voltage of forty-eight volts to an intermediate bus voltage of twelve or six volts.

REFERENCES

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