Letters

DC-DC Converter Synthesis: An Inverse Problem

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***Abstract*—The inverse problem for the dc–dc converters refers to synthesizing converter topologies from a specified voltage gain expression. Though the flux balance principle is widely used in the analysis of dc–dc converters, its application as a synthesis tool has not been explored. This letter describes a mathematical approach to synthesize converter topologies from a required voltage gain expression by utilizing the principle of inductor flux balance. At first, the general form of gain expression for second-order converters is derived. From the general form of gain expression, the inverse problem is formulated by identifying the governing equations. The mathematical formulation of the inverse problem and highlighting challenges involved in solving it are the primary subjects of this article. To outline these challenges, a probable solution strategy of this inverse problem is presented. In order to derive a converter topology, at first, the appropriate flux balance equations are determined, and then the circuit topology is derived to establish the required flux balance. In contrast to the forward problem, the solution to the inverse problem is neither direct nor unique. Hence, getting the optimum closed-form solution to this inverse problem is an open-ended challenge with many possible approaches.**

***Index Terms*—Converter synthesis, dc–dc converter, flux balance principle, topology.**

I. Introduction

DC–DC converters are the fundamental building blocks in the power supply of various applications , such as data centers, consumer appliances, renewable integrations, energy harvesting, and transportation, etc., [1]–[3]. These dc–dc converters are used to match the load voltage (V_o) requirement with that available from the sources (V_{in}). Hence, the voltage gain $(G = V_{\text{in}}/V_o)$ of the dc-dc converter is of utmost importance. The principle of inductor flux balance [4] is one of the fundamental tools used in the analysis of dc–dc converters and to determine their voltage gain (G). Inverse problem [5], [6] broadly refers to the process of obtaining the system parameters from a known or required output. For dc–dc converters, the inverse problem translates to synthesizing a converter topology for a specified conversion ratio. These synthesis methods can be used to identify a pool of converters for any required voltage conversion ratio. Once the family of converters with the required voltage conversion ratio is identified, the most suitable converter can be decided based on the application. Different approaches to synthesize non-isolated Pulse Width Modulated (PWM) dc–dc converters have been reported in the literature, several of them are summarized below.

Mostly, the converter topologies are derived intuitively or by combining existing topologies. A Three terminal canonical cell-based synthesis method was reported in [7]–[9]. The canonical cell is connected between the input and output port in different configurations to yield different converter topologies, and afterward, the converter gain is evaluated. In [10], a family of converter topologies was extracted from one basic converter topology by flipping the three-terminal cell. Another popular method is to connect basic topologies, such as buck, boost, etc., in cascade to achieve the required gain. Layer and graft schemes were proposed in [11] to form single stage converters from cascaded two-stage converters by merging the switches and energy storage elements. Reduced redundant power processing concept was used to derive non-cascading structure-based converters [12]–[15]. Here, different configurations are chosen to ensure that power processed by one stage is not entirely processed by the other. This concept was initially applied to power factor correction applications and was later extended to dc–dc converters [13]–[15]. The principle of graph theory [16] and duality [17] were also used as synthesis tools to derive different voltage and current source PWM converters. The isomorphic relationship between voltage and current source converters was discussed in [18]. Though these methods identify the topological relationship among converters, the objective of finding a converter topology from a specified gain expression is not addressed. An analytical synthesis theory was proposed in [19] and [20], where the main idea was to find an algebraic representation of the converter topology based on its network states. These algebraic representations were used to synthesize converters with desired properties. This synthesis method involves a complex procedure including the formation of network graphs, cut-sets, a large number of

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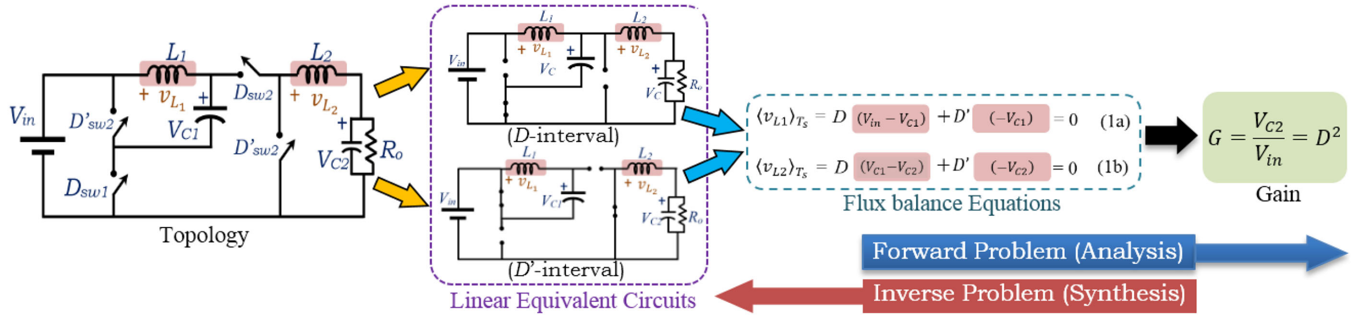

Fig. 1. Application of the principle of inductor volt-sec balance: Forward and reverse prospective.

computations (matrix operations), and a comprehensive search through a pool of possible converters to identify the suitable converter topology.

Though several synthesis methods were proposed in the literature, the application of flux balance equation in an inverse problem, i.e., the application of the principle of flux balance as a synthesis tool, has not been explored. A flux balance principle-based synthesis method was proposed in [21] and [22], where a process to synthesize converter topologies from the specified conversion ratio was reported. However, the work was limited, mostly, to first order converters, and only a few second-order topologies were identified intuitively from a large set of possible configurations. The exact mathematical formulation of the inverse problem was also not reported.

In this letter, the inverse problem of gain-oriented converter synthesis, utilizing the principle of flux balance as an elemental tool, is introduced. This letter is focused around the mathematical formulation of the inverse problem and highlights the complexities involves in solving it. The governing equations for the inverse problem are identified and the physical significance of all the terms present in the equations is given. A few probable solution methods are also reported.

II. Fundamental Assumptions

1) The circuit elements of the converter are considered to be ideal. The order "*n*" is defined as the order of the gain expression, i.e., number of *LC* pairs present in the converter.
2) The switching frequency is assumed to be much higher compared to the *L–C* resonant frequency. Therefore, the voltage across the capacitors remains constant during a switching period. The inductor currents are assumed to be continuous, i.e., continuous conduction mode operation is assumed.
3) There is only one input source (V_{in}) and only one control variable (*D*). The converter output voltage is a function of V_{in} and *D*, i.e., the output voltage is load-independent.

III. General Form of Equations for Second-Order Converters

The principle of inductor volt-sec balance states that for a converter operating in equilibrium the net volt-sec in a switching period, i.e., the net area under the inductor voltage curve, must be zero. In general, this principle is used to evaluate the voltage gain (*G*) of any PWM converter topology. A well-known quadratic buck topology [23] is shown in Fig. 1. The switches D_{sw1} and D_{sw2} are on during the *D* interval, whereas the complementary switches D'_{sw1} and D'_{sw2} are turned on during the *D'* interval. As shown in Fig. 1, the topology toggles between two linear circuits to achieve the required gain. The flux balance equations across both the inductors are given as (1) in Fig. 1. These two flux balance equations jointly decide the gain (*G*) of the converter.

A. General Form of Gain Expression

Second-order converters are defined as the converters with two sets of *LC* pairs. Let the input voltage be V_{in}. The voltages across the capacitors C_1 and C_2 are denoted as V_{C_1} and V_{C_2}, respectively. The switching period (T_s) is the inverse of the switching frequency (f_s). Under continuous conduction mode (CCM) operation, the switching period (T_s) is divided into two sub-intervals, DT_s and $D'T_s$. Where, the duty ratio (D) varies between 0 and 1, and $D+D' = 1$. The voltage across the inductors during any interval can be expressed as a linear combination of input voltage (V_{in}) and capacitor voltages (V_{C_1} and V_{C_2}). Therefore, the general form of the volt-sec equations for the inductors (L_1 and L_2) are given as follows:

$$\langle v_{L_1}\rangle_{T_s} = (\alpha_{10}.V_{\text{in}} + \alpha_{11}.V_{C1} + \alpha_{12}.V_{C2}).D + (\beta_{10}.V_{\text{in}} + \beta_{11}.V_{C1} + \beta_{12}.V_{C2}).D' = 0 \quad (2a)$$

$$\langle v_{L_2}\rangle_{T_s} = (\alpha_{20}.V_{\text{in}} + \alpha_{21}.V_{C1} + \alpha_{22}.V_{C2}).D + (\beta_{20}.V_{\text{in}} + \beta_{21}.V_{C1} + \beta_{22}.V_{C2}).D' = 0. \quad (2b)$$

The (2a) and (2b) have twelve coefficients of the form α_{ij} and $\beta_{ij}, i = 1, 2; j = 0, 1, 2$. The parameter "$i$" refers to the inductors and the parameter "j" refers to the voltage stiff elements, viz., V_{in}, V_{C_1}, and V_{C_2}. As shown in Fig. 2, α and β refer to D and D' interval, respectively. The values of these parameters are chosen from the set {-1, 0, 1}, which corresponds to the manner in which V_{in}, V_{C_1}, and V_{C_2} are connected across the inductor. For the topology shown in Fig. 1, the values of α_{ij} and β_{ij}

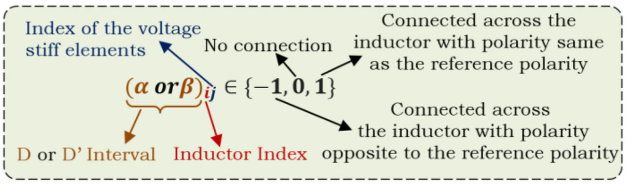

Fig. 2. Significance of α_{ij} and β_{ij} present in volt-sec equation.

parameters are as follows:

$$\begin{bmatrix}\alpha_{10}\\ \alpha_{11}\\ \alpha_{12}\end{bmatrix} = \begin{bmatrix}1\\ -1\\ 0\end{bmatrix}, \begin{bmatrix}\beta_{10}\\ \beta_{11}\\ \beta_{12}\end{bmatrix} = \begin{bmatrix}0\\ -1\\ 0\end{bmatrix}, \begin{bmatrix}\alpha_{20}\\ \alpha_{21}\\ \alpha_{22}\end{bmatrix} = \begin{bmatrix}0\\ 1\\ -1\end{bmatrix}, \text{and} \begin{bmatrix}\beta_{20}\\ \beta_{21}\\ \beta_{22}\end{bmatrix} = \begin{bmatrix}0\\ 0\\ -1\end{bmatrix}. \quad (3)$$

The voltage conversion ratio or the voltage gain (G) of a converter is defined as the ratio of output voltage (V_{C_2}) to the input voltage. It can be obtained by solving (2a), (2b) and using $D' = 1\text{-}D$. G can be expressed as the ratio of two second-order polynomials in D as follows:

$$G = \frac{V_{C2}}{V_{in}} = \frac{N_2D^2 + N_1D + N_0}{M_2D^2 + M_1D + M_0} \quad (4)$$

The expressions for coefficients M_0-M_2 and N_0-N_2 of (4) are given in (5)–(7) and (8)–(10), shown at the bottom of this page, respectively.

B. Forward Problem

The forward problem (see e.g., Fig. 1) is defined as the process of obtaining the gain (G) for a given converter topology. An example of the forward problem is depicted in Fig. 1. Typically, when the topology is specified, the flux balance equations across the inductors can be obtained and G is evaluated directly. For the topology shown in Fig. 1, the coefficients M_0-M_2 and N_0-N_2 are evaluated by putting values of α_{ij} and β_{ij} coefficients from (3) in (5)–(10) and the resulting gain $G = D^2$.

The important observations from this discussion are as follows.

1) The linear functions of V_{in}, V_{C_1},and V_{C_2} present in the flux balance equations [highlighted in (1)] decide the gain (G).
2) For the forward problem, all the (α_{ij} and β_{ij}) coefficients are known and gain can be evaluated directly by solving the expressions (4)–(10).
3) As the process involves simplifying expressions, for any given topology, the voltage gain is unique.

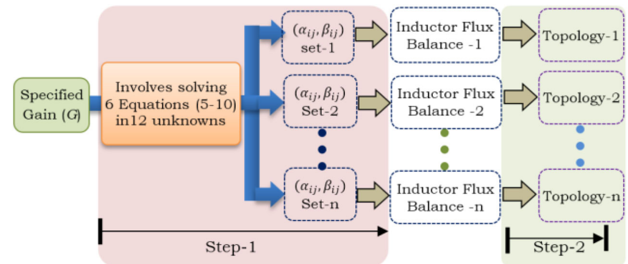

Fig. 3. Pictorial representation of the inverse problem.

IV. The Inverse Problem

The inverse problem is defined as the process of obtaining a converter topology from a given voltage gain expression. This inverse problem is formulated around the principle of inductor flux balance, and it can be divided into two parts, as depicted in Fig. 3.

A. Gain to Flux Balance Equations

In order to derive a converter topology that achieves the required voltage gain (G), at first, the flux balance equations are to be determined. Once G is specified, the terms M_0-M_2 and N_0-N_2 are obtained uniquely by comparing the specified G to (4). The known values of M_0-M_2 and N_0-N_2 converts the expressions (5)–(10) to six equations in twelve unknowns (α_{ij}, β_{ij}).

The important observations that can be made from these set of (5)–(10) are as follows.

1) The equations of the numerator coefficients (5)–(7) and denominator coefficients (8)–(10) are similar, the only difference being in the increase of index "j" by one in (8)–(10) compared to (5)–(7).
2) The terms (α_{11}, β_{11}) and (α_{21}, β_{21}) appear in the expressions of both the numerator and denominator coefficients. However, (α_{10}, β_{10}), (α_{20}, β_{20}) are exclusive to the numerator (5)–(7) and (α_{12}, β_{12}), (α_{22}, β_{22}) are exclusive to the denominator expressions (8)–(10).

$$(\beta_{21}\beta_{10} - \beta_{11}\beta_{20}) = N_0 \quad (5)$$

$$(\alpha_{21}\beta_{10} - \alpha_{20}\beta_{11}) + (\alpha_{10}\beta_{21} - \alpha_{11}\beta_{20}) - 2(\beta_{21}\beta_{10} - \beta_{11}\beta_{20}) = N_1 \quad (6)$$

$$(\alpha_{10}\alpha_{21} - \alpha_{11}\alpha_{20}) + (\alpha_{20}\beta_{11} - \alpha_{21}\beta_{10}) + (\alpha_{11}\beta_{20} - \alpha_{10}\beta_{21}) + (\beta_{21}\beta_{10} - \beta_{11}\beta_{20}) = N_2 \quad (7)$$

$$(\beta_{22}\beta_{11} - \beta_{12}\beta_{21}) = M_0 \quad (8)$$

$$(\alpha_{22}\beta_{11} - \alpha_{21}\beta_{12}) + (\alpha_{11}\beta_{22} - \alpha_{12}\beta_{21}) - 2(\beta_{22}\beta_{11} - \beta_{12}\beta_{21}) = M_1 \quad (9)$$

$$(\alpha_{11}\alpha_{22} - \alpha_{12}\alpha_{21}) + (\alpha_{21}\beta_{12} - \alpha_{22}\beta_{11}) + (\alpha_{12}\beta_{21} - \alpha_{11}\beta_{22}) + (\beta_{11}\beta_{22} - \beta_{12}\beta_{21}) = M_2 \quad (10)$$

3) If $[\alpha_{11}\ \beta_{11}] = \pm[\alpha_{21}\ \beta_{21}]$ or $[\alpha_{11}\ \beta_{11}] = [0\ 0]$, or $[\alpha_{21}\ \beta_{21}] = [0\ 0]$, then the gain expression shown in (4) degenerates to a first-order gain. If $[\alpha_{1j}\ \beta_{1j}] = \pm[\alpha_{2j}\ \beta_{2j}]$, for all values of "*j*," then in both the cases, the inductors have the same volt-sec equation. This is equivalent to two first-order converters in parallel. Hence, the gain in (4), degenerates to a first-order gain.
4) If $[\alpha_{10}\ \beta_{10}] = [0\ 0]$, and $[\alpha_{20}\ \beta_{20}] = [0\ 0]$, then the converter is disconnected from the input. Similarly, if $[\alpha_{12}\ \beta_{12}] = [0\ 0]$ and $[\alpha_{22}\ \beta_{22}] = [0\ 0]$, then the converter is disconnected from output. So, both of these combinations are invalid.

In general, when variables are real numbers, six equations in twelve unknowns lead to infinitely many solutions. However, in this case, as the values of the parameters α_{ij} and β_{ij} are limited to the set {-1, 0, 1}, the number of possible solution is also limited. Even though the number of solution is limited, getting the solution to this set of equations is difficult. Moreover, the obtained solution is also not unique. In other words, for a specified voltage gain (*G*), many sets of $(\alpha_{ij}, \beta_{ij})$ can be obtained, which leads to multiple pairs of flux balance equations following (2).

B. Flux Balance Equations to Circuit Topology

Once the flux balance equations are identified, the circuit topology has to be derived. This process involves connecting the circuit elements in a specific orientation and placing switches optimally. More than one circuit topology can be designed to produce the required flux balance equation. However, the objective is to minimize the number of switches used. Apart from this, sometimes, though the flux balance equations can be written mathematically, their physical realization is not possible. This is due to the specific the combination of voltages V_{in}, V_{C_1}, and V_{C_2}. For example, if $[\alpha_{10}\ \alpha_{11}] = [1\ \ 1]$, and $[\alpha_{20}\ \alpha_{21}] = [1 - 1]$, then the circuit is not realizable as two conflicting voltage combinations are required during the same interval.

C. Comparison Between the Forward and the Inverse Problem

The comparison between the forward and the inverse problem, i.e., the analysis and synthesis problems can be summarized as follows.

1) Both the forward and inverse problem utilize the principle of inductor flux balance as the basic tool, and the linear functions of V_{in}, V_{C_1}, and V_{C_2}, present in the flux balance equations, play an important role.
2) Both the forward and inverse problem utilizes (5)–(10). In the forward problem, all the $(\alpha_{ij}, \beta_{ij})$ values are known. Therefore, M_0-M_2 and N_0-N_2 can be evaluated directly. Whereas, in the inverse problem, M_0-M_2 and N_0-N_2 are known. Hence, its solution, i.e., obtaining the values of $(\alpha_{ij}\ \beta_{ij})$, requires solving a set of six equations in twelve unknowns. Therefore, the complexity of solving the inverse problem is significantly higher as compared to the forward problem.
3) The forward problem has a unique solution, i.e., for a given topology, the voltage gain is unique. However, the inverse problem has multiple solutions, and the number of possible solutions also cannot be directly calculated.

This section introduced the inverse problem, its mathematical formulation, and identified the difficulties involve in solving it. A few probable solutions for solving the inverse problem are stated in the next section.

V. Probable Solution Strategies for the Inverse Problem

The process of obtaining the converter topology from the specified conversion gain involves two steps. This section describes a few probable approaches to implement both.

A. Solutions Leading to Flux Balance Equations

As discussed in the earlier, getting the flux balance equation, i.e., the $(\alpha_{ij}, \beta_{ij})$ coefficients, involves solving six equations in twelve unknowns. Though this set of equations cannot be solved directly, a few strategies, as discussed below, can be used.

1) Choosing Some (α_{ij} and β_{ij}) and Evaluating the Rest: In this method, few $(\alpha_{ij}, \beta_{ij})$ parameters are assumed, and the remaining parameters are calculated. When a few parameters were chosen, the number of unknowns reduces. Then equations can be simplified to obtain solutions. However, the effectiveness of this method depends on the initial values chosen. As the coefficients $(\alpha_{11}, \beta_{11})$ and $(\alpha_{21}, \beta_{21})$ appear in both numerator and denominator expressions, they are better suited as initial values. Choosing these values also decouples the denominator and numerator expressions. Hence, they can be solved independently, making the solution process simpler.

As an example, for the converter gain $G = D^2$, $M_0 = 1$, $N_2 = 1$, and M_1, M_2, N_0, N_1 are 0. For these, M_0-M_2 and N_0-N_2 values, the (5)–(10) are solved with the initial values $[\alpha_{11}\ \ \beta_{11}] = [-1 - 1]$, and $[\alpha_{21}\ \ \beta_{21}] = [0 - 1]$, and it leads to four unique solutions as follows:

$$\begin{bmatrix}\alpha_{10}\\ \alpha_{11}\\ \alpha_{12}\end{bmatrix} = \begin{bmatrix}1+X\\ -1\\ Y\end{bmatrix}$$

$$\begin{bmatrix}\beta_{10}\\ \beta_{11}\\ \beta_{12}\end{bmatrix} = \begin{bmatrix}X\\ -1\\ Y\end{bmatrix} \begin{bmatrix}\alpha_{20}\\ \alpha_{21}\\ \alpha_{22}\end{bmatrix} = \begin{bmatrix}1\\ 0\\ -1\end{bmatrix} \begin{bmatrix}\beta_{20}\\ \beta_{21}\\ \beta_{22}\end{bmatrix} = \begin{bmatrix}X\\ -1\\ Y-1\end{bmatrix}$$

where Xϵ {-1, 0}, Yϵ {0, 1}.

The resulting flux balance equations for [X Y] = [0 0] and [-1 1] are shown in Fig. 4.

2) Brute Force Search: Although the choose and solve method gives some solutions, it does not provide comprehensive results. To obtain a comprehensive set of solution, an exhaustive search algorithm may be utilized. The brute-force search or exhaustive search, also known as generate and test, is a general problem-solving algorithm that consists of systematically iterate through all possible candidates for the solution and check whether the particular candidate satisfies the problem statement. For $G = D^2$, the brute force search algorithm results in 176 possible solutions.

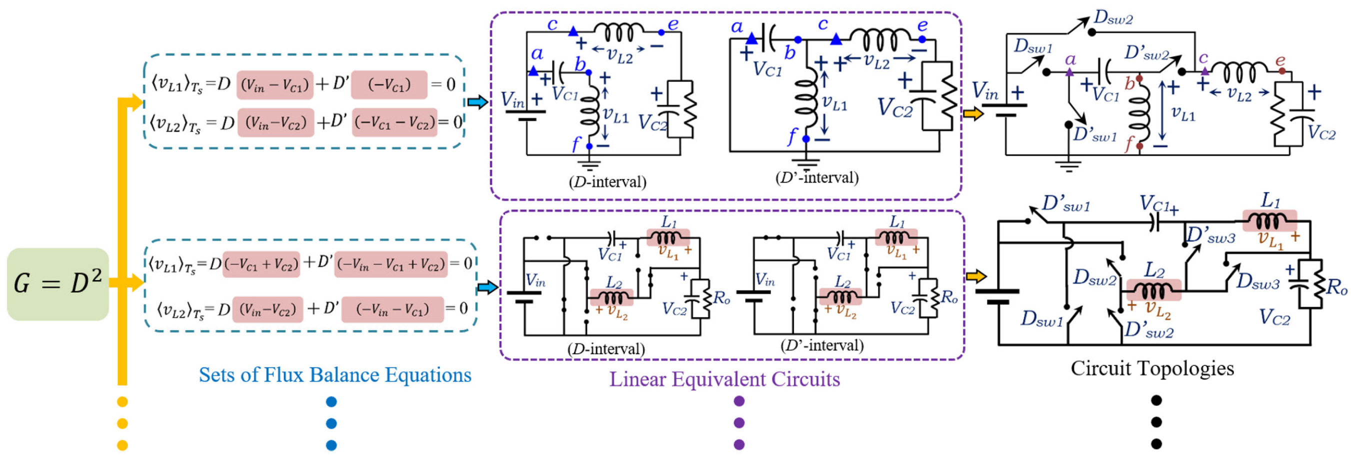

Fig. 4. Pictorial representation of solution to the inverse problem.

B. Getting the Topology From Flux Balance

Once the flux balance equations are known, the next step is to derive the converter topology to achieve these flux balance equations. This process can be divided into two distinct steps as follows.

1) Formation of Linear Circuits Corresponding to the Flux Balance Equation: At first, one linear equivalent circuit is formed corresponding to each interval (*D* and *D'*) of the switching cycle. As an example, let us consider the first set of flux balance equation shown in Fig. 4. In the *D* interval, the voltage impressed across L_1 and L_2 are $(V_{in} - V_{C1})$ and $(V_{in} - V_{C2})$, respectively. Similarly, in the D' interval, the voltage impressed across L_1 and L_2 are $(-V_{C1})$ and $(-V_{C1} - V_{C2})$, respectively. The resulting linear equivalent circuits for both *D* and *D'* intervals are shown in Fig. 4.

2) Obtaining the Converter Topology From the Linear Equivalent Circuits: The procedure to get the converter topology from the linear equivalent circuits involves identifying the switch nodes and inserting switches accordingly. For example, the node "a" in Fig. 4 toggles between V_{in} and ground. Therefore, two switches (D_{sw1} and D'_{sw1}) are inserted to toggle node "*a*" between V_{in} and ground. However, point "*e*" is always connected to V_{C2}. Hence, no insertion of switch is necessary. Similar arguments can be provided for the nodes "a–e."

VI. Conclusion

This letter formalizes the synthesis a converter topology from a required voltage gain expression as an inverse mathematical problem. This inverse problem is formulated around the principle of inductor volt-sec balance by deriving the general form of gain expression for second-order converters. This mathematical formulation of the inverse problem brings out the challenges involved in deriving topologies from a given conversion ratio. A probable solution strategy for this inverse problem is presented in which initially the flux balance equations are obtained from the specified voltage gain expression. From the flux balance equations, linear equivalent circuits for each interval are formed. These linear equivalent circuits are combined with switches to generate the converter topology. For any specified voltage gain expression, different choices of (α_{ij}, β_{ij}) co-efficients lead to different flux balance equations. For example, for a quadratic-buck gain expression, there are 176 different ways the flux balance equation can be formulated. Therefore, many different topologies, with different flux balance equations, are obtained. The solution to the inverse problem is neither direct nor unique, and different mathematical techniques can be applied to solve the inverse problem. Nevertheless, obtaining the optimum closed-form solution to the inverse problem is an exciting direction for additional work in the future.

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