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Dimensionally Consistent Fractional-Order Averaged Modeling and Stability of an Interleaved Bidirectional DC–DC Converter for More-Electric Aircraft

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Abstract

Electrified aircraft power systems require dc–dc interfaces that combine high power density with predictable transient behavior, bidirectional power flow, and balanced current sharing among parallel phases. This paper develops a fractional-order averaged model for a two-phase interleaved synchronous bidirectional dc–dc converter intended for the 270 V/90 V class of more-electric-aircraft distribution systems. Rather than introducing a fractional derivative without regard to the physical dimensions of the conventional model, the proposed formulation employs a reference time constant together with a scaled Caputo representation. This scaling preserves the physical units of the classical averaged model and recovers the conventional integer-order description when the fractional order approaches unity. A common/differential coordinate transformation is introduced to separate the bus-voltage dynamics from the inter-phase imbalance dynamics. This representation yields an explicit Mittag–Leffler description of the current-sharing behavior and enables a closed-form stability analysis. For positive passive circuit parameters and a constant duty ratio, the equilibrium remains independent of the fractional order, while the complete commensurate fractional system is shown to retain asymptotic stability throughout the considered range of fractional orders. Transfer functions describing the duty-to-voltage and differential-duty-to-current dynamics are subsequently obtained in the Laplace domain. Reproducible predictor–corrector simulations at a representative aerospace operating point illustrate how the fractional order influences overshoot, transient decay, and memory-tail behavior without altering the steady-state dc conversion ratio. The proposed framework is therefore intended as a reduced-order memory surrogate for studying transient phenomena in electrified-aircraft power converters. Hardware identification of the fractional order is deliberately separated from the present theoretical development and is identified as the next stage of validation.

Keywords: fractional-order power electronics; Caputo derivative; interleaved bidirectional converter; more-electric aircraft; averaged modeling; current sharing; Mittag–Leffler stability; aerospace dc microgrid.

1 Introduction

The progressive electrification of aircraft has moved power-electronic conversion from an auxiliary role to a structural element of the on-board electrical system. More-electric-aircraft (MEA) architectures replace portions of pneumatic, hydraulic, and mechanical actuation by electrically supplied subsystems; consequently, multiple ac and dc voltage levels coexist and must be coupled with converters that satisfy severe mass, efficiency, reliability, thermal, and power-quality constraints [1, 2, 3]. High-voltage dc buses in the 270 V or ± 270 V class are especially relevant because increasing distribution voltage reduces conductor current for a prescribed power level, but

it also shifts demanding voltage-conversion and protection tasks to the converters [3, 4]. Recent studies continue to identify reliability, high-frequency switching, and wide-bandgap devices as key enablers for future aircraft electrical systems [5, 6, 7].

Interleaving is attractive in this setting because parallel phases distribute semiconductor and magnetic stress while partially cancelling current ripple. A representative MEA architecture using a 270 V/90 V interleaved bidirectional stage followed by an isolated conversion stage has already been studied using classical state-space averaging [4]. That integer-order description is indispensable for design, but it does not provide a compact state-space mechanism for representing long-tail transients or aggregate memory produced by unresolved electromagnetic, dielectric, thermal, and control-side effects. Fractional-order models offer one possible reduced-order description when experimental transients exhibit non-exponential relaxation. Fractional circuit and converter models have been investigated for buck, buck-boost, and general dc-dc structures, with both fractional elements and fractional dynamic operators used to represent non-ideal behavior [10, 11, 9, 12, 13, 8].

A recurring modeling difficulty is dimensional consistency. Writing ${}^C D_t^\alpha x = Ax + Bu$ with the same matrix A used in an integer-order model assigns units $s^{-\alpha}$ to the left side but s^{-1} to the state matrix on the right. One can instead postulate fractional inductors and capacitors with generalized units, but that changes the interpretation of the hardware parameters. The present paper follows a different route: it treats the fractional dynamics as a reduced-order memory lifting of an already identified classical averaged model and introduces a reference time τ_c so that

$${}^C D_t^\alpha x(t) = \tau_c^{1-\alpha} (Ax(t) + Bu(t)), \quad 0 < \alpha \leq 1. \quad (1)$$

This construction has three useful properties: the units are preserved, the classical averaged model is recovered exactly for $\alpha = 1$, and the equilibrium set is unchanged by the fractional order.

The paper concentrates on modeling and analysis rather than controller synthesis. Its main contributions are: (i) a dimensionally consistent Caputo lifting of a two-phase interleaved bidirectional converter; (ii) an exact common/differential decomposition that exposes the inter-phase current-sharing mode; (iii) existence, equilibrium, and fractional stability results; (iv) closed-form transfer functions in s^α ; and (v) reproducible numerical experiments that isolate the effect of α from the dc operating point. No claim is made that a particular value of α is intrinsic to an aerospace converter. In an experimental program, α must be estimated from data and compared against integer-order alternatives by an explicit identification criterion.

2 Aerospace converter setting and classical averaged model

2.1 Two-phase interleaved synchronous stage

We consider a non-isolated two-phase synchronous bidirectional stage connecting a stiff high-voltage bus V_H to a lower-voltage dc link $v(t)$. The same switching cell can support signed inductor current; hence power reversal is represented by the operating point and external current demand rather than by a different state equation. For the modeling results below, continuous-conduction operation and ideal complementary switching within each leg are assumed, while an effective series resistance $r_L > 0$ accounts for inductor copper loss and dominant conduction loss.

For phase duty ratios $d_1, d_2 \in [0, 1]$, the continuous-time averaged equations in the forward buck operating convention are

$$L\dot{i}_1 = d_1 V_H - v - r_L i_1, \quad (2)$$

$$L\dot{i}_2 = d_2 V_H - v - r_L i_2, \quad (3)$$

$$C\dot{v} = i_1 + i_2 - \frac{v}{R} - i_d(t), \quad (4)$$

where i_d denotes an additional signed dc-link disturbance current. The model remains valid locally

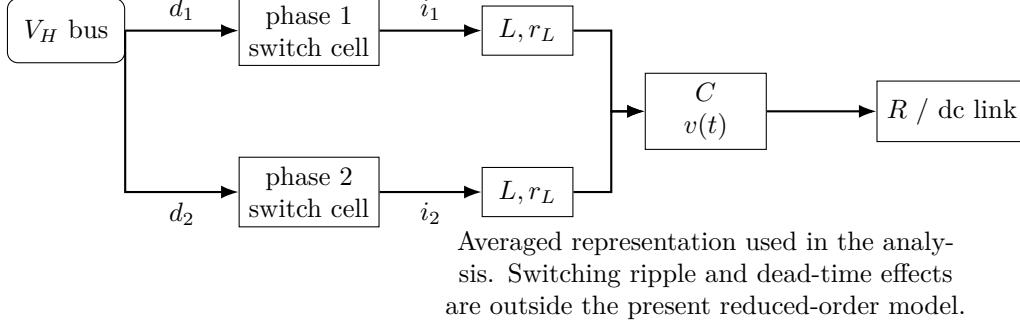


Figure 1: Reduced averaged architecture of the two-phase interleaved bidirectional dc-dc stage.

for bidirectional power flow as long as the synchronous switching realization permits signed phase current and the selected operating point remains in continuous conduction.

With

$$x = \begin{bmatrix} i_1 & i_2 & v \end{bmatrix}^T, \quad u = \begin{bmatrix} d_1 & d_2 & i_d \end{bmatrix}^T,$$

Equations (2)–(4) take the form

$$\dot{x} = Ax + B\nu, \quad (5)$$

with

$$A = \begin{bmatrix} -r_L/L & 0 & -1/L \\ 0 & -r_L/L & -1/L \\ 1/C & 1/C & -1/(RC) \end{bmatrix}, \quad B = \begin{bmatrix} V_H/L & 0 & 0 \\ 0 & V_H/L & 0 \\ 0 & 0 & -1/C \end{bmatrix}. \quad (6)$$

State-space averaging is standard in PWM converter analysis; the present objective is not to replace that framework, but to construct a fractional extension that remains anchored to it.

3 Fractional-order lifting

3.1 Caputo derivative

Definition 3.1. For $0 < \alpha < 1$ and an absolutely continuous scalar function y , the Caputo derivative is

$${}^C D_t^\alpha y(t) = \frac{1}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} y'(\xi) d\xi. \quad (7)$$

For $\alpha = 1$ we set ${}^C D_t^1 y = y'$.

The Caputo form is convenient because classical initial data $y(0)$ enter directly and its Laplace transform is

$$\mathcal{L}\{{}^C D_t^\alpha y(t)\}(s) = s^\alpha Y(s) - s^{\alpha-1} y(0).$$

Standard references on fractional differential equations and control include [14, 15, 16]; existence and structural properties of fractional initial-value problems are developed in [17].

3.2 Reference-time scaling

Let $\tau_c > 0$ be a fixed reference time associated with the modeling bandwidth. We define the fractional lifting of (5) by

$${}^C D_t^\alpha x(t) = k_\alpha (Ax(t) + B\nu(t)), \quad k_\alpha := \tau_c^{1-\alpha}. \quad (8)$$

The factor k_α has units $s^{1-\alpha}$; since A has units s^{-1} , $k_\alpha A$ has units $s^{-\alpha}$, matching the left-hand side. At $\alpha = 1$, $k_1 = 1$ and (8) reduces exactly to (5).

Remark 3.2 (Interpretation). Equation (8) is a reduced-order memory model, not a claim that the ideal inductor and capacitor literally obey the same fractional constitutive law. Fractional capacitors and inductors provide a different modeling route and have been studied in converter circuits [10, 11, 8]. Here, L , C , r_L and R retain their classical engineering units, while α and τ_c parameterize departure from the classical transient law.

3.3 Existence and uniqueness

Proposition 3.3. *Let $0 < \alpha \leq 1$, $\tau_c > 0$, and let $\nu : [0, T] \rightarrow \mathbb{R}^3$ be continuous. For every initial state $x(0) = x_0 \in \mathbb{R}^3$, system (8) has a unique continuous solution on $[0, T]$. If ν is bounded on $[0, \infty)$, the solution exists globally.*

Proof. The right-hand side

$$f(t, x) = k_\alpha(Ax + B\nu(t))$$

is continuous in t and globally Lipschitz in x , because

$$\|f(t, x) - f(t, y)\| \leq k_\alpha \|A\| \|x - y\|.$$

The standard Caputo initial-value theory therefore yields a unique local solution. Global continuation follows because the vector field has at most linear growth in x and the input is bounded [17, 15]. $\square$

4 Equilibrium and modal decomposition

4.1 Symmetric steady state

Consider constant equal duty ratio $d_1 = d_2 = d$ and $i_d = 0$. A symmetric equilibrium has $i_1^* = i_2^* = i^*$. Setting the right-hand sides of (2)–(4) to zero gives

$$i^* = \frac{v^*}{2R}, \quad v^* = \frac{dV_H}{1 + r_L/(2R)}. \quad (9)$$

Because the positive factor k_α multiplies the complete vector field, this equilibrium does not depend on α .

Proposition 4.1 (Order-independent dc operating point). *For any $0 < \alpha \leq 1$, the equilibrium set of (8) under a constant input ν^* is identical to the equilibrium set of the classical averaged model (5).*

Proof. An equilibrium satisfies $0 = k_\alpha(Ax^* + B\nu^*)$. Since $k_\alpha > 0$, this is equivalent to $Ax^* + B\nu^* = 0$. $\square$

4.2 Common and differential currents

Define

$$i_\Sigma = i_1 + i_2, \quad i_\Delta = i_1 - i_2, \quad (10)$$

and

$$d_\Sigma = \frac{d_1 + d_2}{2}, \quad d_\Delta = \frac{d_1 - d_2}{2}. \quad (11)$$

Then (8) is equivalent to

$${}^C D_t^\alpha i_\Sigma = k_\alpha \left(-\frac{r_L}{L} i_\Sigma - \frac{2}{L} v + \frac{2V_H}{L} d_\Sigma \right), \quad (12)$$

$${}^C D_t^\alpha i_\Delta = k_\alpha \left(-\frac{r_L}{L} i_\Delta + \frac{2V_H}{L} d_\Delta \right), \quad (13)$$

$${}^C D_t^\alpha v = k_\alpha \left(\frac{1}{C} i_\Sigma - \frac{1}{RC} v - \frac{1}{C} i_d \right). \quad (14)$$

Thus the inter-phase current-sharing mode is dynamically decoupled from the output-voltage mode in the averaged model.

Corollary 4.2 (Exact current-sharing law). *If $d_1 = d_2$, then $d_\Delta = 0$ and the phase-current mismatch satisfies*

$$i_\Delta(t) = i_\Delta(0) E_\alpha \left(-k_\alpha \frac{r_L}{L} t^\alpha \right). \quad (15)$$

For $\alpha = 1$, (15) reduces to $i_\Delta(t) = i_\Delta(0) e^{-(r_L/L)t}$.

Proof. Equation (13) with $d_\Delta = 0$ is the scalar Caputo equation ${}^C D_t^\alpha z = -az$, $a = k_\alpha r_L/L > 0$. Its solution is the Mittag-Leffler function $z(t) = z(0) E_\alpha(-at^\alpha)$. $\square$

5 Fractional stability

For constant equal duty ratio, shift the state by the equilibrium. The common-mode subsystem is

$${}^C D_t^\alpha \begin{bmatrix} \tilde{i}_\Sigma \\ \tilde{v} \end{bmatrix} = k_\alpha A_\Sigma \begin{bmatrix} \tilde{i}_\Sigma \\ \tilde{v} \end{bmatrix}, \quad A_\Sigma = \begin{bmatrix} -r_L/L & -2/L \\ 1/C & -1/(RC) \end{bmatrix}. \quad (16)$$

The differential mode has eigenvalue $-k_\alpha r_L/L$.

Theorem 5.1 (Asymptotic stability for all commensurate orders). *Assume $L, C, R, r_L, \tau_c > 0$. Then the equilibrium (9) of the unforced equal-duty system is asymptotically stable for every $0 < \alpha \leq 1$.*

Proof. For the 2×2 matrix A_Σ ,

$$\begin{aligned} \text{tr}(A_\Sigma) &= -\frac{r_L}{L} - \frac{1}{RC} < 0, \\ \det(A_\Sigma) &= \frac{r_L}{LRC} + \frac{2}{LC} > 0. \end{aligned}$$

Hence both eigenvalues of A_Σ lie in the open left half-plane. Multiplication by the positive scalar k_α does not alter their arguments. The differential-mode eigenvalue $-k_\alpha r_L/L$ also lies on the negative real axis. Therefore every eigenvalue λ of the full fractional state matrix satisfies

$$|\arg(\lambda)| > \frac{\alpha\pi}{2}, \quad 0 < \alpha \leq 1.$$

By the Matignon criterion for commensurate fractional systems, the equilibrium is asymptotically stable [19, 20]. $\square$

Remark 5.2. Theorem 5.1 separates two questions that are often mixed in numerical studies. The fractional order changes the transient kernel, but it does not destabilize this passive averaged plant merely by taking $\alpha < 1$. Instability may still arise after closing a feedback loop, including digital delays, saturations, constant-power loads, or switching nonlinearities; those mechanisms are intentionally reserved for the control-oriented sequel to this work.

6 Laplace-domain representation

Let zero initial conditions be used for transfer-function calculations and define

$$q_\alpha(s) = \frac{s^\alpha}{k_\alpha}.$$

Taking Laplace transforms of (12) and (14), with $i_d = 0$, yields the common-duty to output-voltage transfer function

$$G_{vd,\alpha}(s) := \frac{V(s)}{D_\Sigma(s)} = \frac{\frac{2V_H}{LC}}{\left(q_\alpha(s) + \frac{r_L}{L}\right)\left(q_\alpha(s) + \frac{1}{RC}\right) + \frac{2}{LC}}. \quad (17)$$

Similarly, the differential-duty to current-imbalance map is

$$G_{\Delta,\alpha}(s) := \frac{I_\Delta(s)}{D_\Delta(s)} = \frac{2V_H k_\alpha / L}{s^\alpha + k_\alpha r_L / L}. \quad (18)$$

At $\alpha = 1$, $q_1(s) = s$ and the standard second-order averaged duty-to-voltage transfer function is recovered. The poles of (17) are roots in s^α , which is the frequency-domain manifestation of the non-exponential memory kernel.

7 Aerospace benchmark and numerical protocol

7.1 Representative operating point

The numerical experiment uses a 270 V/90 V operating class motivated by MEA conversion studies such as [4]. The parameters in Table 1 are representative modeling values, not measurements from a certified converter or a hardware prototype.

Table 1: Representative parameters used in the reproducible numerical study.

Quantity	Symbol	Value
High-voltage bus	V_H	270 V
Nominal low-voltage bus	v^*	90 V
Phase inductance	L	250 μ H
Output capacitance	C	1 mF
Effective phase resistance	r_L	40 m Ω
Nominal resistive load	R	2.7 Ω
Reference time	τ_c	1 ms
Nominal phase current	i^*	16.667 A
Nominal duty ratio	d_0	0.335802
Post-step duty ratio	d_1	0.355802

The post-step equilibrium predicted by (9) is

$$v_1^* = \frac{d_1 V_H}{1 + r_L / (2R)} = 95.3603 \text{ V}. \quad (19)$$

The fact that this target is common to all values of α provides a useful check: any order-dependent dc shift would signal either a different fractionalization or a numerical artifact.

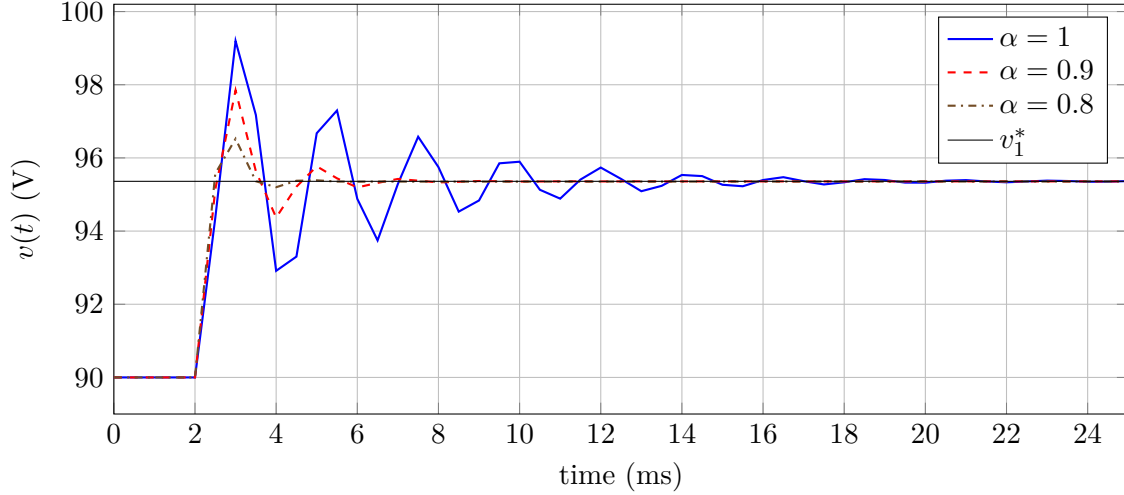


Figure 2: Output-voltage response to a common duty-ratio step at $t = 2$ ms. Coordinates are generated by the predictor–corrector scheme described in the text.

7.2 Predictor–corrector discretization

For ${}^C D_t^\alpha x = f(t, x)$, the numerical coordinates used below were generated with an Adams-type predictor–corrector method of the Diethelm–Ford–Freed family [18]. If $t_n = nh$, the predictor is

$$x_{n+1}^P = x_0 + \frac{h^\alpha}{\Gamma(\alpha + 1)} \sum_{j=0}^n b_{j,n+1} f(t_j, x_j), \quad (20)$$

where

$$b_{j,n+1} = (n + 1 - j)^\alpha - (n - j)^\alpha.$$

The corrector is

$$x_{n+1} = x_0 + \frac{h^\alpha}{\Gamma(\alpha + 2)} \left[f(t_{n+1}, x_{n+1}^P) + \sum_{j=0}^n a_{j,n+1} f(t_j, x_j) \right], \quad (21)$$

with the standard fractional Adams weights. No random data are used.

8 Numerical results

8.1 Duty-ratio step

At $t = 2$ ms, the common duty ratio is increased from d_0 to d_1 while the initial condition is the nominal equilibrium. Figure 2 compares $\alpha \in \{1, 0.9, 0.8\}$. The integer-order response exhibits the largest oscillatory overshoot. Under the chosen reference-time normalization, decreasing α suppresses the first overshoot and introduces a slower algebraic memory tail. The limiting voltage remains close to the common value v_1^* , as predicted by Proposition 4.1.

The peak values extracted from the same runs are summarized in Table 2. These numbers should be read as properties of the chosen reduced model and parameter set, not as universal superiority claims for smaller fractional orders.

8.2 Inter-phase current imbalance

To isolate the differential mode, the converter is initialized at the nominal total current and voltage but with

$$i_1(0) = i^* + 4 \text{ A}, \quad i_2(0) = i^* - 4 \text{ A},$$

Table 2: Duty-step transient indicators for the representative benchmark.

α	peak voltage (V)	peak time (ms)	overshoot relative to v_1^* (%)
1.0	99.353	3.10	4.19
0.9	97.883	2.95	2.65
0.8	96.755	2.83	1.46

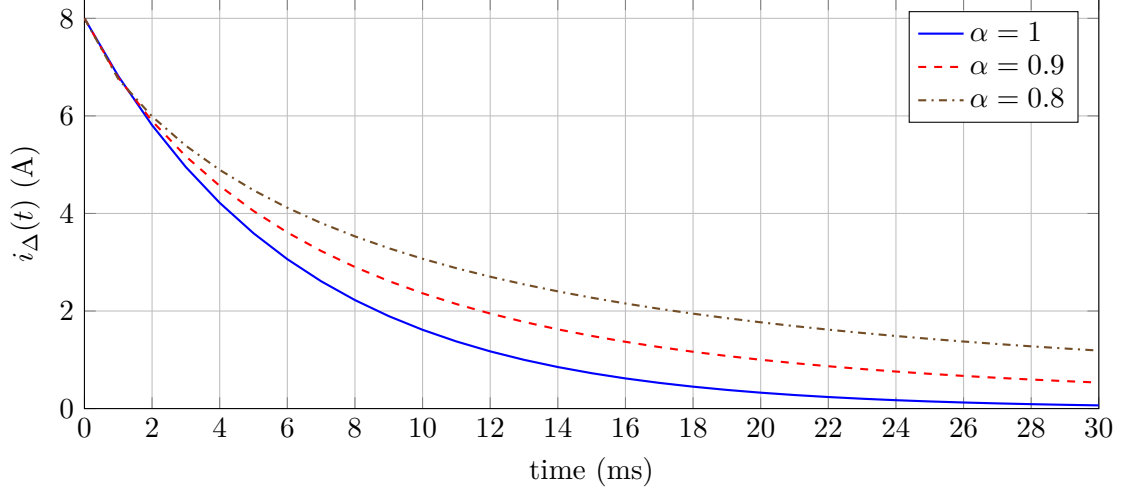


Figure 3: Decay of phase-current imbalance under equal duty ratio. The integer-order exponential law is recovered at $\alpha = 1$; fractional orders exhibit a Mittag-Leffler tail.

so $i_\Delta(0) = 8$ A. Equal duty ratios are then applied. Figure 3 agrees with the Mittag-Leffler result (15). The fractional models display a slower long-time decay than the exponential integer-order mode, an important point for fault-detection or current-sharing supervision: a smaller α need not imply faster decay of every internal state even if it reduces output-voltage overshoot in a particular maneuver.

8.3 Step-size check

A short refinement test was performed for the duty-step case. Table 3 reports the peak and the value at 12 ms. The fractional runs are essentially unchanged under halving of the step size in the reported digits; the integer-order case converges more slowly in the endpoint value because the plant retains lightly damped oscillations over the finite observation window.

Table 3: Predictor-corrector refinement check for the duty-step experiment.

α	h (μ s)	peak v (V)	peak time (ms)	$v(12\text{ ms})$ (V)
0.8	100	96.7594	2.70	95.3525
0.8	50	96.7543	2.80	95.3526
0.8	25	96.7548	2.83	95.3526
0.9	100	97.9224	2.90	95.3568
0.9	50	97.8825	2.95	95.3567
0.9	25	97.8834	2.95	95.3568
1.0	100	99.3603	3.00	95.6961
1.0	50	99.3541	3.10	95.7314
1.0	25	99.3532	3.10	95.7365

9 Engineering interpretation for MEA use

The mathematical results have a direct systems interpretation. First, interleaving introduces an internal differential mode that does not appear in a single-phase model. Equation (15) gives that mode explicitly and shows that equal duty commands alone do not erase current mismatch instantaneously. The decay law depends on r_L/L , the fractional order, and the reference-time scaling. Second, the dc conversion ratio does not change with α in the proposed lifting. This is desirable when α is used only to capture memory in transient data: parameter identification can modify the dynamic shape without corrupting the classical operating-point design.

For an aircraft converter, however, a model is useful only if it survives tests against phenomena omitted from the derivation. At least four extensions are needed before hardware-level claims are justified. Switching ripple and interleaving phase shift should be restored in a switched or harmonic model; wide-bandgap device losses and temperature dependence should be introduced if SiC or GaN hardware is considered [6, 7]; constant-power and tightly regulated loads should be tested because they can generate negative incremental impedance; and α should be identified from measured transients under multiple operating conditions. A single fitted maneuver is insufficient to establish a genuine memory law.

The present model nevertheless provides a useful baseline for the planned paper series. A robust fractional controller can be designed against (17) without changing the plant definition; fault-tolerant reconfiguration can use the decoupled imbalance coordinate i_Δ ; and multiobjective optimization can subsequently trade transient performance against semiconductor losses, thermal stress, and redundancy. Keeping those questions separate avoids conflating plant modeling with controller tuning or fault-management logic.

10 Limitations and validation path

Three limitations are central. First, the study is averaged and therefore does not resolve switching harmonics, dead time, device capacitances, or EMI. Second, the fractional order is phenomenological. The paper demonstrates mathematical consistency and identifiable dynamic consequences, but it does not assert that $\alpha = 0.8$ or 0.9 is a material constant of the converter. Third, the numerical study is synthetic and model-consistent. It validates the implementation of the proposed equations, not an aerospace prototype.

A defensible experimental program would record $v(t)$ and phase currents $i_1(t), i_2(t)$ during duty, load, and power-flow reversals over temperature. Competing integer and fractional models should be estimated on one subset of the data and evaluated on held-out maneuvers using residual whiteness, prediction error, and information criteria. Only if the fractional model provides repeatable out-of-sample improvement should the order α be interpreted as a useful engineering descriptor.

11 Conclusion

A dimensionally consistent fractional-order averaged model has been developed for a two-phase interleaved bidirectional dc–dc converter representative of a more-electric-aircraft power interface. The scaling $\tau_c^{1-\alpha}$ preserves the physical units of the classical state-space model and guarantees exact recovery of the integer-order equations at $\alpha = 1$. The common/differential transformation exposes a decoupled current-sharing mode with an explicit Mittag–Leffler solution. Positive passive parameters place all plant eigenvalues in the open left half-plane; the Matignon sector condition then yields asymptotic stability for every commensurate order $0 < \alpha \leq 1$. The equilibrium and dc conversion ratio are independent of α , whereas transient overshoot and long-time relaxation are order dependent. Reproducible numerical experiments illustrate both effects for a 270 V/90 V benchmark.

The principal value of the formulation is therefore not a claim that fractional dynamics universally improve converter performance. It is a mathematically controlled way to introduce memory into an established averaged model without altering its dc design equations. The next step is experimental identification and comparison against integer-order alternatives; robust control and fault-tolerant reconfiguration should then be built on the validated plant rather than introduced prematurely.

Declarations

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Data and code availability. No external experimental data are used in this version. Numerical coordinates in the figures are generated from the stated model and predictor–corrector discretization and are embedded directly in this `main.tex` source.

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