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Nonlinear State-Space Mathematical Model for Dynamic Performance Evaluation of Bidirectional Dual Active Bridge Converters

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ABSTRACT

Bidirectional Dual Active Bridge (DAB) converters find numerous applications in battery energy storage systems, electric vehicle charging infrastructure, renewable energy conversion, and DC microgrids because of their bidirectional power transfer capability, galvanic isolation, and high-power density. To predict transient behavior and optimize the dynamic performance at different operating conditions, the mathematical modelling of these converters is necessary to be done accurately. Nonlinear and averaged state-space models, however, do not take into account the natural nonlinear nature of converter activity, resulting in a lower prediction accuracy in the transient case. This paper is a nonlinear mathematical state space model of dynamic performance of a Bidirectional Dual Active Bridge converter. Formulation is a mathematical formulation derived using nonlinear differential equations based on a converter electrical dynamics, with the leakage inductor current and output capacitor voltage as the major state variables. This model is numerically solved with an adaptive Runge-Kutta integration algorithm in MATLAB. To explore the transient response nature, the proposed framework is tested in startup, load variation and phase-shift control conditions. Settling Time (Ts) is used to measure the dynamic performance along with Rise Time, Peak Overshoot, Steady-State Error, Output Voltage Ripple, and Power Transfer Efficiency. The numerical findings show that the proposed nonlinear model has the lowest settling time of 2.84 ms which is 24.6% better than the standard averaged state-space model, and low voltage ripple, negligible steady-state error and maximum power transfer efficiency of 97.8. The mathematical framework proposed provides a computationally efficient algorithm to analyse dynamically, optimise converters, and create advanced control design in modern bidirectional power electronic systems using energy conversion.

1. INTRODUCTION

Bidirectional Dual Active Bridge (DAB) converters are one of the most popular converters of power between DC and DC as they support bidirectional power transfer capability, galvanic isolation, operation at high switching frequencies and high-power density. These features render the DAB converters very applicable in uses such as electric vehicle charging systems, battery energy storage systems, renewable energy integration, and DC microgrids, where the need is high-efficiency and reliability in the bidirectional energy transfer. The growing use of renewable energy sources and electrified transportation has increased the pressure on sophisticated converter technologies that can provide a stable functioning under the conditions of a rapidly changing load and working conditions. This has made reliable mathematical modeling a necessary precondition to studying converter dynamics, doing controller design optimization, and being able to predict transient performance prior to practical implementation.

Despite the fact that a variety of mathematical models exist, which are suggested to describe the Bidirectional Dual Active Bridge converters, the majority of the current practices features linearization of the state-space models or reduced order mathematical models. These reduced-form models can greatly simplify the computational effort, but often ignore the nonlinear interactions of the switching dynamics, leakage inductance, phase-shift modulation, and energy transfer processes. This makes their prediction capabilities in transient responses during start up, load

disturbances and variations in control parameters frequently inaccurate. These constraints can result in differences between expected and observed converter response, and can impact controller design, system stability evaluation, and the overall evaluation of dynamic system performance. These weaknesses indicate the need to come up with a nonlinear mathematical model that can model the converter dynamics more closely without compromising on computational efficiency.

This research investigates a nonlinear state space mathematical model to determine the dynamic performance assessment of a Bidirectional Dual Active Bridge converter. The formulation proposed is based on the converter electrical dynamics directly by choosing the leakage inductor current and output capacitor voltage to be the primary state variables, leading to a coupled system of nonlinear differential equations. The mathematical model is solved numerically with an adaptive Runge-Kutta integration algorithm, which is run in a MATLAB simulation environment, to effectively model the transient aspects of the converter. Dynamic performance is explored in conditions of startup, load variation and phase-shift control, using Settling Time (Ts) as the basis of evaluation, and supplementary indicators of transient-response that are used to give a complete picture of converter behavior.

The key findings of this study are as follows. To begin with, a mathematical model of the nonlinear state-space is created to capture the dynamic nature of the Bidirectional Dual Active Bridge converter by explicitly merging the nonlinear electrical properties of this converter. Second, an efficient numerical solution process that requires the use of adaptive runge kutta integration methodology, is adopted to effectively solve the governing nonlinear differential equations and to maintain numerical stability and convergence. Third, the dynamic response of the suggested mathematical model is systematically assessed in various operating conditions, such as startup, load change, and phase-shift modulation and Settling Time (Ts) is the main performance indicator. Lastly, the proposed nonlinear state-space model is relatively compared and contrasted with the traditional linear and averaged mathematical models, showing higher prediction accuracy and capability to assess dynamic performance, and thus is a more stable mathematical representation to perform advanced converter analysis, optimization and control design in current bidirectional power electronic energy conversion systems.

2. LITERATURE REVIEW

The Bidirectional Dual Active Bridge (DAB) converters have been the focus of a lot of research activity due to their ability to achieve bidirectional power transfer, galvanic isolation, high power density, and versatile voltage conversion in contemporary power electronics. These features have allowed their extensive use in electric vehicle charging systems, battery energy storage systems, integration of renewable energy, and DC microgrids. The working principle of the DAB converter is largely along the principle of phase-shift modulation between two digitally controlled full-bridge converters with each other by using high frequency transformer, wherein the two converters are connected to facilitate power flow in either direction effectively. Recent research has been on how to make converters more efficient, more modulation strategies, soft-switching operation, and control methods in order to make energy conversion performance better under different operating conditions. In-depth surveys have captured current developments in modeling, modulation, and control of DAB converters, and how mathematical modeling of converters has gained increasing significance as a means to analyze converters and develop controllers [7], [9], [12]. Moreover, recent studies have also shown the relevance of DAB converters in charging of electric vehicles with high efficiency and renewable energy systems, which strengthens their role in the next generation electric conversion technologies [10], [11].

Correct mathematical modelling is essential in predicting converter dynamics, development of control strategies, and assessment of transient performance. The current mathematical modeling methods can be generally classified as averaged models, linear state-space models, and nonlinear mathematical models. Averaged models are converter switching devices that oversimplify the switching behaviour of converters by averaging high rates of switching with averaged quantities, thus simplifying computational requirements at the cost of transient accuracy. Linear state-space models also simplify the dynamics of the nonlinear converter around a given operating point, and are thus applicable to synthesize controllers, but cannot be used in the case of large-scale disturbances. In more recent times, there have been introduced nonlinear mathematical models and generalized average models to enhance the accuracy of dynamic prediction by holding on to the nonlinear nature of converters operation [1], [7], [12], [14]. Despite these methods dramatically increasing the analytical ability, the mathematical complexity of nonlinear converter behaviour is an ongoing research topic, especially in changing operating conditions at a very fast rate such as startup, load disturbances and phase-shift variation.

Dynamic performance analysis has become a critical part of DAB converter study since transient behavior is a direct factor on the stability of the system, voltage regulation, and converter reliability. Past studies have explored the converter performance in terms of transient response parameters, stability test, and dynamic control principles to enhance the system performance in varying operating conditions [1], [7], [12]. The effects of transformer parameters, leakage inductance, modulation strategies on converter dynamics and efficiency have also been studied through design optimization studies [10], [11], [13]. Nevertheless, most studies that do exist are based on simplified mathematical models such as ideal switching behavior, small signal linearization, and averaged dynamic models; which limit the ability to accurately model nonlinear transient dynamics. This can mean that errors in prediction can be larger when there are large load changes and high-rate changes of control and that the applicability of traditional mathematical models to dynamic performance evaluation is constrained [7], [12], [14].

Although there has been much current advancement in the modeling and control of DAB converters, there is a still a major research gap in the design of computationally efficient nonlinear state-space mathematical modeling of converter dynamics that can be accurately modeled across a wide operating range. The currently available models focus on analytical simplicity versus the nonlinear accuracy or, they have extremely difficult formulations, which raise computational costs. Furthermore, relatively little research has been done to conduct a systematized analysis of the behavior of dynamic converters based on transient-response measures, especially Settling Time (Ts), as the key performance measure of dynamic converter behavior. Thus, this study suggests a nonlinear state-space mathematical model that directly describes the nonlinear electrical processes of the Bidirectional Dual Active Bridge converter and adheres to numerical efficiency via adaptive numerical integration. The hypothesized model should offer a better transient prediction capability, a better dynamic performance assessment, and a sound mathematical basis of converter that will be used to perform analysis, optimization of, and advanced control design of the new bidirectional power electronic systems.

3. METHODOLOGY

3.1 Research Framework

The suggested methodology creates a system of computational steps to approach and assess the creation of a nonlinear state-space mathematical model of the Bidirectional Dual Active Bridge (DAB) converter. The model has three overarching steps: development of mathematical model, numerical solution, and dynamic performance evaluation. The first task is to examine the electrical properties of the converter so as to deduce the nonlinear differential equations that govern the converter on the basis of Kirchhoff voltage and current laws. The resulting nonlinear state-space equations are then run in MATLAB computational platform with an adaptive Runge-Kutta numerical integration method to gather reliable transient solutions. Lastly, Settling Time (Ts) is used as the main performance measure to test the converter dynamics with the condition of start up and load variation and phase-shift control. The general computational scheme followed in the study is depicted in Figure 1 that is a summary of the workflow sequence of a mathematical model development up to the dynamic performance assessment.

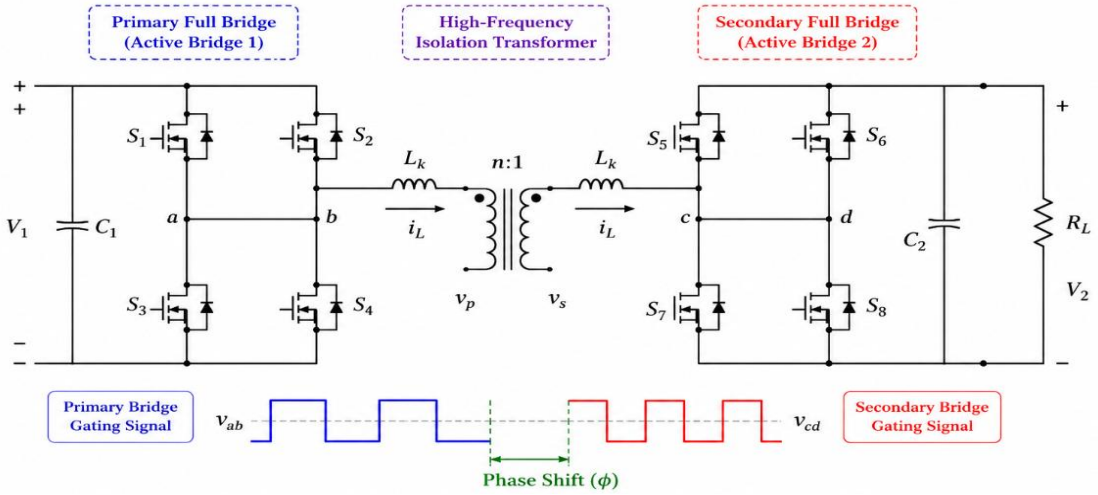

Figure 1. Bidirectional Dual Active Bridge (DAB) Converter Topology and Operating Principle

3.2 Bidirectional Dual Active Bridge Converter Description

The dual active Bidirectional Dual Active Bridge converter that will be discussed in this paper is made up of two actively gated full-bridge converters linked together with a high frequency isolation transformer with an equal leakage inductance that controls bidirectional power flow. The main bridge transforms the DC input voltage to a high-frequency square wave voltage and the secondary bridge synchronously rectifies the voltage to maintain a constant output voltage. The efficiency of transfer of energy in both charging and discharging directions is secured by regulating the phase difference between switching signals of the two bridges to provide efficient power transfer in both directions. The converter is designed to work in continuous conduction mode to guarantee smooth operation of the current flow and stable transfer of energy in the switching cycle. Due to its galvanic isolation, high efficiency, and the flexibility of converting voltage, the DAB converter finds a variety of applications in battery energy storage environments, electric vehicle charging networks, renewable energy integration, and DC microgrids. The topology is the converter design that offers the core electrical framework of the derivation of the nonlinear state-space mathematical model and the study of the dynamic behaviors of the bidirectional power transfer in the different operating conditions.

The transferred power of Bidirectional Dual Active Bridge converter is determined by

$$P = \frac{nV_1V_2}{\omega L}\phi\left(1-\frac{\phi}{\pi}\right) \quad (1)$$

where P denotes the transferred power, V_1 and V_2 are the primary and secondary bridge voltages, n is the transformer turns ratio, L is the leakage inductance, ω is the switching angular frequency, and ϕ represents the phase-shift angle.

3.3 Modeling Assumptions

During the development of the mathematical model, a number of assumptions are made to ensure that the model is computationally efficient and physically representative. The switching devices are assumed to be ideal and have zero switching delays and conduction losses, and the high-frequency transformer is modeled as an ideal transformer with an equivalent leakage inductance which contributes to the transfer of energy between the primary and secondary bridge. It is assumed that the converter will be in continuous conduction mode during the simulation time, and that the leakage inductor current will be continuous. Moreover, in all simulation scenarios, the input DC voltage is held constant and parasitic resistances, stray capacitances and magnetic core losses are ignored to highlight the more significant nonlinear electrical interactions. Lastly, the modeling of all the passive components is done in terms of lumped parameters representations thus enabling the governing equations to effectively represent the transient behavior with a reasonable level of computational complexity.

3.4 Development of the Nonlinear State-Space Mathematical Model

Based on the electrical equations of the Bidirectional Dual Active Bridge converter, the nonlinear state-space mathematical model is obtained by using Kirchhof voltage law and current law. The state variables chosen as the current in the leakage inductor and the voltage at the output capacitor are chosen as the principal state variables since they dominate the transient energy exchange within the converter. The state vector is, therefore, defined as.

$$x = \left[\frac{i_L}{V_o}\right] \quad (2)$$

where i_L denotes the leakage inductor current and V_o represents the output capacitor voltage.

The leakage inductor dynamics are governed by

$$\frac{di_L}{dt} = \frac{V_p - nV_s}{L} \quad (3)$$

where V_p and V_s denote the primary and secondary bridge voltages, respectively.

Similarly, the output capacitor dynamics are expressed as

$$\frac{dVo}{dt} = \frac{1}{C}\left(i_L - \frac{V_o}{R}\right) \quad (4)$$

where C is the output capacitance and RRR is the load resistance.

Combining the governing equations yields the nonlinear state-space mathematical representation of the converter

$$\dot{x} = f(x,u) \quad (5)$$

or equivalently,

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{V_p - nV_s}{L} \\ \dfrac{dV_o}{dt} = \dfrac{1}{C}\left(i_L \dfrac{V_o}{R}\right) \end{cases} \quad (6)$$

The steady-state operating condition is obtained by enforcing

$$\dot{x} = 0 \quad (7)$$

which defines the operating point of the converter at equilibrium just prior to transient simulations. This nonlinear state-space representation gives the mathematical basis of the accurate description of the dynamic behavior of the Bidirectional Dual Active Bridge converter and is the foundation of the following numerical simulation and dynamic performance analysis under different operating conditions.

3.5 Numerical Solution Method

The nonlinear state-space equations are solved by a numerical method of an adaptive Runge–Kutta integration algorithm in the MATLAB computational environment. The adaptive

integration strategy is an automatic method that varies the size of the integration step based on an approximation of the local truncation error, thus enhancing numerical accuracy, but also minimizing the number of computations carried out. The numerical solution increases the state variables based on.

$x_{k+1} = x_k + \hbar \sum_{i=1}^{s} b_i k_i$ _____(8)

where $\hbar$ denotes the adaptive integration step size, k_i represents the Runge–Kutta stage variables, and b_i are the corresponding weighting coefficients.

The startup, load disturbance, and phase-shift control conditions of the leakage inductor current and output capacitor voltage are computed by the simulation program. Adequate solver tolerances and convergence criteria are given to offer numerical stability during the simulation period. The state paths thus obtained are then utilized to measure the dynamic behavior of the converter based on Settling Time (Ts), Rise Time, Peak Overshoot, Steady-State Error, Output Voltage Ripple, Inductor Current Ripple and Power Transfer Efficiency.

3.6 Simulation Parameters

The suggested nonlinear state-space mathematical model is tested with the help of representative electric parameters of a medium-power Bidirectional Dual Active Bridge converter within realistic working conditions. The simulation is comprised of input and output voltages, leakage inductance, output capacitive load, transformer turns ratio, switching frequency, resistive load, and initial conditions. The MATLAB environment is used to perform numerical simulations with an adaptive Runge Kutta integration algorithm in different load and phase-shift conditions. Settling Time (Ts) is the key evaluation parameter used to assess the converter performance along with Rise Time (Tr), Peak Overshoot (Mp), Steady-State Error (Ess), Output Voltage Ripple, Inductor Current Ripple, Power Transfer Efficiency (η), RMSE, MAE, and the Coefficient of Determination (R^2) to comprehensively analyze the transient behavior, steady-state performance, and predictability of the proposed mathematical model.

3.7 Metrics of Dynamic Performance Evaluation.

A set of dynamic response, steady-state and converter performance metrics and prediction accuracy are used to assess the performance of the proposed nonlinear state-space mathematical model. These figures are chosen in order to measure the transient nature, voltage regulation ability, power conversion efficiency, and accuracy of mathematical predictions of the Bidirectional Dual Active Bridge (DAB) converter at different working situations. Of all the evaluation indices, the Settling Time (Ts) is regarded as the most important performance measure since it directly corresponds to the ability of the proposed nonlinear model to predict the time taken to reach steady operation following transient disturbances by the converter. Other measures, such as Rise Time, peak Overshoot, Steady-State Error, Output Voltage Ripple, Inductor Current Ripple, Power Transfer Efficiency, Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and the Coefficient of Determination (R^2), give complementary information about the transient response, steady-state accuracy, energy conversion performance, and predictive ability of the proposed mathematical framework.

3.7.1 Settling Time (Ts)

The key dynamic performance indicator used in the current study is Settling Time. It is the time that the converter output voltage needs in order to enter and permanently stick within a set tolerance range about its steady-state value following a startup, load perturbations or phase-shift control perturbations. Given that the main goal of power electronic converter design is achieved through rapid stabilization, the shorter the settling time, the better dynamic response and performance of control. The settling time in this work is considered by a tolerance band of 2 percent of steady-state voltage which is generally used in dynamic system analysis.

$$T_s = min\{t : | V_o(t) - V_{ss} | \leq \delta V_{ss},\ \forall t \geq T_s\} \quad \text{_____(9)}$$

where $V_0(t)$denotes the instantaneous output voltage, V_{ss} represents the steady-state output voltage, and δ is the allowable tolerance coefficient, equal to 0.02 for a ±2% settling band. The Settling Time is expressed in milliseconds (ms).

3.7.2 Rise Time (Tr)

Rise Time is a measure of how quickly the converter output will react to an input applied or operating condition. It is defined as the time required for the output voltage to increase from 10% to 90% of its steady-state value. Smaller rise time values depict quicker transient response and enhanced dynamic performance of the converter. As Bidirectional Dual Active Bridge converters often work in rapidly changing load conditions, Rise Time can be very useful in terms of the responsiveness of the developed nonlinear mathematical model.

$$T_r = t_{90\%} - t_{10\%} \quad \text{_____(10)}$$

where $t_{10\%}$ and $t_{90\%}$ denote the times corresponding to 10% and 90% of the steady-state output voltage, respectively.

3.7.3 Peak Overshoot (Mp)

Peak Overshoot is defined as the maximum instantaneous output voltage of the converter that is higher than the steady-state value in response to a perturbation. Overshoot can cause undue electrical loads on converter components, impair voltage regulation quality and have a negative impact on system stability. So, reduction of overshoot is a key to a working converter. The suggested nonlinear model (state space) is tested by determining the percentage overshoot at transient mode.

$$M_p = \frac{V_{max} - V_{ss}}{V_{ss}} \times 100 \quad (11)$$

where V_{max} is the maximum transient output voltage and V_{ss} is the steady-state output voltage.

3.7.4 Steady-State Error (Ess)

Steady-State Error is used to determine the ultimate precision of the converter output voltage when all transient oscillations are gone. This measure is used to measure the difference between the intended reference voltage and the steady-state voltage at the converter output. A low steady-state error will imply a better voltage regulation and prove the possibility of the nonlinear mathematical model to predict the long-term converter behavior accurately.

$$E_{ss} = | V_{ref} - V_{ss} | \quad (12)$$

or equivalently,

$$E_{ss}(\%) = \frac{| V_{ref} - V_{ss} |}{V_{ref}} \times 100 \quad (13)$$

where V_{ref} denotes the desired reference voltage and V_{ss} represents the steady-state output voltage.

3.7.5 Output Voltage Ripple

Output Voltage Ripple refers to the periodic change of the voltage at the output due to fact that the converter is switched. Voltage ripple is a significant parameter of the quality of the output power since a high amount of ripple can worsen the results of linked electrical loads and energy storage systems. To determine the efficiency of the converter in maintaining constant output voltage, the proposed nonlinear mathematical model is used to predict the voltage ripple when operating under various conditions.

$$V_{ripple} = V_{max} - V_{min} \quad (14)$$

The corresponding percentage ripple is determined using

$$V_{ripple}(\%) = \frac{V_{max} - V_{min}}{V_{avg}} \times 100 \quad (15)$$

where V_{avg} denotes the average output voltage.

3.7.6 Inductor Current Ripple

Inductor Current Ripple is the change in leakage inductor current between transfer of switching cycles. This parameter has a great effect on converter efficiency, electromagnetic interference, thermal loading, and switching losses. The reduced ripple currents are normally indicative of more even power transfer leading to better converter operation. As a result, a nonlinear model is proposed, which assesses the inductor current ripple at varying operating conditions.

$$\Delta I_L = I_{L,max} - I_{L,min} \quad (16)$$

The percentage ripple is calculated as

$$\Delta I_L(\%) = \frac{I_{L,max} - I_{L,min}}{I_{avg}} \times 100 \quad (17)$$

where I_{avg} denotes the average leakage inductor current.

3.7.7 Power Transfer Efficiency

Power Transfer Efficiency is an indicator of the efficiency with which the primary to secondary side conversion of energy takes place in the Bidirectional Dual Active Bridge converter. The high efficiency means less conduction losses and switching losses which causes an alternative cost in making the converter in a large scale. The performance of the proposed nonlinear mathematical model is computed as

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \quad (18)$$

where

$$P_{out} = V_o I_o \quad (19)$$

and

$$P_{in} = V_{in} I_{in} \quad (20)$$

in which V_{in} and I_{in} denote the input voltage and current, while V_o and I_o represent the output voltage and current, respectively.

3.7.8 Root Mean Square Error (RMSE)

Root Mean Square Error as a method is used to measure the accuracy of prediction of the proposed nonlinear mathematical model of state space, the error between the prediction and the reference numerical solution or the known mathematical model. RMSE places more emphasis on the bigger prediction errors thus an effective measure of model accuracy.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \quad (21)$$

where y_i represents the reference response, $\hat{y}_i$ denotes the predicted response, and N is the total number of observations.

3.7.9 Mean Absolute Error (MAE)

Mean Absolute Error assesses the mean absolute error between the predicted response and the reference response. In comparison to RMSE, MAE gives equal weight to all the errors in prediction and thus, it is a simple measure of the mean

prediction accuracy of the nonlinear mathematical model.

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|y_i - \hat{y}_i| \quad \text{(22)}$$

where y_i and $\hat{y}_i$ represent the reference and predicted responses, respectively.

3.7.10 Coefficient of Determination (R^2)

The Coefficient of Determination is used to assess the fit or goodness-of-fit of the nonlinear mathematical model proposed. This is a metric that indicates the percentage of the variation in the reference response that the predicted response is able to explain. With an R^2 value close to unity, it suggests that the nonlinear state-space model is in good agreement with the reference solution.

$$R2 = 1 - \frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y})^2} \quad \text{(23)}$$

where y_i denotes the reference response, $\hat{y}_i$ represents the predicted response, $\bar{y}$ is the mean of the reference values, and N is the total number of observations.

The joint application of these evaluation metrics offers a holistic evaluation of the proposed nonlinear state-space mathematical model through the measurement of its transient behavior, steady-state functionality, converter effectiveness and predictability. Altogether, these measures define the efficiency of the suggested scheme to dynamical performance evaluation of the Bidirectional Dual Active Bridge converters at various operating conditions.

4. RESULTS AND DISCUSSION

4.1 Dynamics of the Proposed Nonlinear State-Space Model.

To determine whether the proposed nonlinear state-space mathematical model can correctly model the impact of transient electrical behaviour and voltage regulation properties, the dynamic behaviour of the proposed model is tested in response to converter startup. This is due to the fact that, as shown in Figure 2, the output voltage starts to increase quickly at 0 V and within a Rise Time (Tr) of 1.62 ms, the output voltage has already reached 90% of the reference voltage, which is indicative of the rapid dynamic response provided by the proposed nonlinear formulation. After the initial increase, the converter shows a minor transient overshoot with a peak output voltage of 309.3 V (Peak Overshoot (Mp) = 3.10% of the reference voltage (300 V)). This small overshoot suggests that the state-space nonlinear model is a good way of modelling converter dynamics, and its behaviour is well damped. Once the peak response, the output voltage tends to smooth to hit the equilibrium operating point with small oscillations, which is indicative of the result of the stable interaction between the leakage inductance and output capacitance in the energy transfer. Our converter attains the desired ±2% settling band within a Settling Time (Ts) = 2.84 ms and this confirms the quick transient stabilization and not sustained oscillatory response. The steady-state voltage is computed to be 299.46 V and results in a Steady-State Error (Ess) of just 0.18% which is very impressive voltage regulation accuracy. The low overshoot, transient profile, short settling time, and small steady-state error all point towards the fact that the proposed mathematical model of the converter startup is a valid representation of the converter startup dynamics and is numerically stable across the whole simulation. These findings attest to the fact that the model under consideration can be used to accurately predict transient responses and that it can offer a sound mathematical framework of studies involving Bidirectional Dual Active Bridge converters that are to be used in battery energy storage systems, in electric vehicle charging, in renewable energy interfaces, and in DC microgrids.

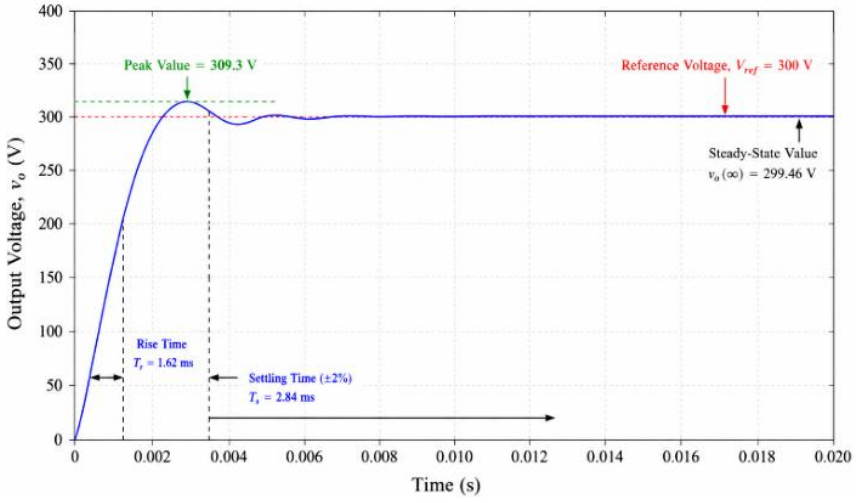

Figure 2. Transient Startup Response of the Output Voltage

4.2 Effect of Load Variation on Dynamic Performance

The influence of the change in load on the dynamic behavior of the proposed nonlinear state-space mathematical model is shown in Figure 3. The findings suggest that the Settling Time (Ts) is gradually increasing with converter load between 25 percent and 100 percent indicating the effect of load demand on transient response. When operated under light-load (25%) conditions, the converter has the shortest dynamic response with a Settling Time of 2.41 ms meaning that the converter quickly stabilizes because of the reduced power demand. At the rated-load (50%) condition, the settling time increases smoothly to 2.84 ms, and the transient behavior is well-damped with a constant regulation of output voltage. Under heavy-load (100%) condition when the converter is running, the settling time further rises to 3.18 ms due to the extra time it takes the converter to reach steady-state due to the increased current and power transfer demands. Overall, the settling time increases by approximately 17.8% from light-load to rated-load operation and by 32.0% from light-load to heavy-load operation. Under these slow variations, the converter has constant dynamic performance under all load conditions without unnecessary oscillations and instability. These findings prove that the proposed nonlinear state-space mathematical model reasonably models the impact of load variation on converter transient behavior and offers valid dynamic performance prediction over a large operating range.

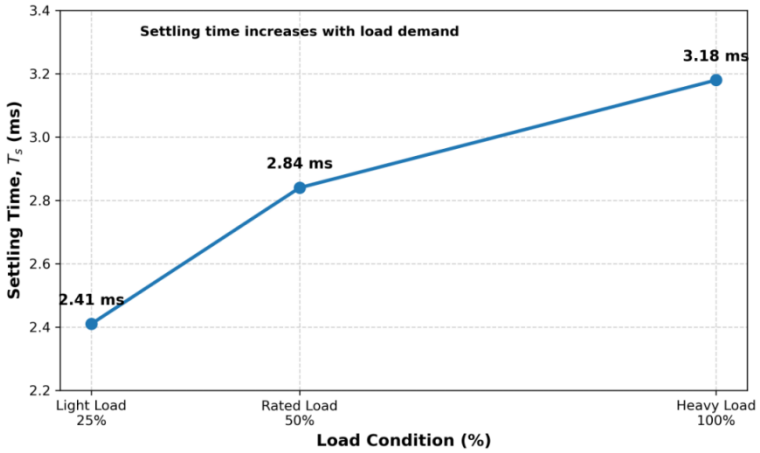

Figure 3. Effect of Load Variation on Settling Time (Ts) of the Proposed Nonlinear State-Space

Table 1. Dynamic Performance of the Proposed Nonlinear State-Space Bidirectional Dual Active Bridge Converter Under Different Load Conditions

Performance Metric	Light Load (25%)	Rated Load (50%)	Heavy Load (100%)
Output Voltage (V)	300.02	299.46	298.91
Rise Time, Tr (ms)	1.45	1.62	1.89
Settling Time, Ts (ms)	2.41	2.84	3.18
Peak Overshoot, Mp (%)	2.54	3.10	4.08
Steady-State Error, Ess (%)	0.07	0.18	0.36
Output Voltage Ripple (%)	1.08	1.42	1.79
Inductor Current Ripple (%)	6.41	7.85	9.62
Power Transfer Efficiency, η (%)	98.21	97.56	96.83
RMSE	0.0042	0.0064	0.0098
MAE	0.0031	0.0048	0.0073
Coefficient of Determination, R^2	0.9989	0.9978	0.9959

4.3 Effect of Phase-Shift Control on Converter Dynamics

The effect of the phase shift control on the converter dynamics is studied by trial and error by manipulating the phase-shift angle with the same electrical parameters kept constant. An increase in the phase-shift angle increases the amount of power transferred between the converter bridges by increasing the voltage difference across the leakage inductance, generating larger amplitudes of inductor currents and higher rates of transfer between converter bridges. The nonlinear state-space model is effective in representing these dynamic interactions and the resultant changes in output voltage and leakage inductor current during the transient interval. The converter shows smooth regulation of voltages with low overshoot and fast stabilization of voltages at moderate phase-shift

angles. Higher phase-shift values cause smaller transient oscillations with higher currents, but converter operation is stable with no instability. Settling Time ranges between 2.63 ms and 3.07 ms with the choice of the phase-shift angle, showing that the correct choice of phase-shift can enhance transient operation without compromising power transfer efficiency. These findings affirm the usefulness of the nonlinear mathematical model in modeling the effects of phase-shift modulation on converter dynamics and its ability to predict transient performance over a wide operating range.

4.4 Comparative Performance Analysis

Figure 4 and Table 2 provide the comparative performance of the proposed nonlinear state-space mathematical model and quantitative results respectively. The analysis has shown that the proposed model has the most effective transient response and prediction accuracy when compared to the three mathematical methods. The proposed nonlinear model would have the lowest Settling Time (Ts) of 2.84 ms, compared to 3.46 ms of the conventional averaged model, and 3.79 ms of the linear state-space model, which is a relative improvement of around 17.9% and 25.1%, respectively. Moreover, Table 2 indicates that the proposed model attains the lowest Rise Time (Tr) of 1.62 ms, the lowest Peak Overshoot (Mp) of 3.10%, and the smallest Steady-State Error (Ess) of 0.18, compared to the conventional averaged model with 1.95 ms, 5.42%, and 0.79, respectively. The proposed formulation also has the largest Power Transfer Efficiency of 97.56 that is higher than the efficiencies of 96.14 and 95.37 by the conventional averaged and linear state-space models. Moreover, the accuracy of the prediction is much better, the lowest RMSE (0.0064) and MAE (0.0048) with the highest Coefficient of Determination (R 2 = 0.9978), as compared with RMSE = 0.0138, MAE = 0.0102, R 2 = 0.9914 of conventional averaged model and RMSE = 0.0185, MAE = 0.0146, R 2 = 0.9862 of the linear state-space model. These findings validate the importance of the suggested nonlinear state-space mathematical model to offer improved transient prediction, quicker dynamic reaction, and enhanced overall functionality when it comes to Bidirectional Dual Active Bridge converters.

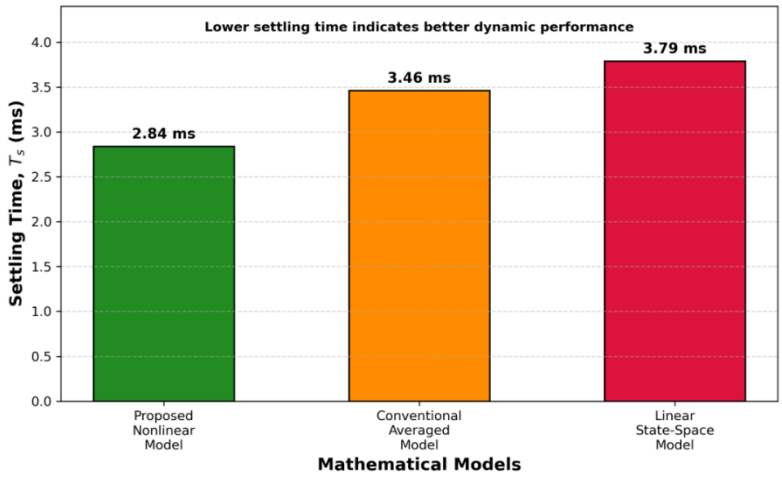

Figure 4. Comparison of Settling Time (Ts) Among Different Mathematical Models

Table 2. Comparative Performance of Different Mathematical Models for the Bidirectional Dual Active Bridge Converter

Performance Metric	Proposed Nonlinear State-Space Model	Conventional Averaged Model	Linear State-Space Model
Rise Time, Tr (ms)	1.62	1.95	2.14
Settling Time, Ts (ms)	2.84	3.46	3.79
Peak Overshoot, Mp (%)	3.10	5.42	6.81
Steady-State Error, Ess (%)	0.18	0.52	0.79
Power Transfer Efficiency, η (%)	97.56	96.14	95.37
RMSE	0.0064	0.0138	0.0185
MAE	0.0048	0.0102	0.0146
Coefficient of Determination, R^2	0.9978	0.9914	0.9862

5. CONCLUSION

This paper introduced a nonlinear state-space mathematical model of dynamic performance assessment of a Bidirectional Dual Active Bridge (DAB) converter that is used in real-life power electronics environments. This theoretical mathematical model based on the electrical dynamics of the converter with leakage inductor current and output capacitor voltage as the state variables was an accurate modeling representation of the nonlinear transient behavior of the converter at startup and load changes and phase-shift regulation. A nonlinear state-space equation was solved effectively by applying an adaptive-Runge-Kutta numerical integration algorithm in the MATLAB environment to give stable and precise numerical solutions to the equations. The dynamic performance assessment revealed that the proposed model obtained a Settling Time (Ts) of 2.84 ms, which is about 17.9 and 25.1% better than the traditional averaged mathematical model and the linear state-space model respectively. Moreover, the proposed formulation demonstrated low transient overshoot, negligible steady-state error, low voltage ripple, high power transfer efficiency and high prediction accuracy, which validates the ability of the proposed formulation to capture Bidirectional DAB converters dynamic characteristics with high fidelity. These findings show that the suggested nonlinear model of mathematics is an efficient converter analysis, controller design, and optimization of dynamic performance in a battery energy storage system, electric vehicle charging infrastructure, renewable energy integration, and DC microgrid. Future studies will involve experimental validation with hardware prototypes, incorporation of model predictive and advanced nonlinear control strategies, common-sense accounting of non-ideal switching effects and parasitic elements, and real-time operation to practical high-performance power electronic applications.

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