International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING
ISSN:2147-6799 www.ijisae.org Original Research Paper

Forecasting Stability in Super-Lift Converters Utilizing Averaging Technique

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Submitted: 11/03/2024 **Revised:** 27/04/2024 **Accepted:** 04/05/2024

Abstract: This work presents a thorough investigation into DC-DC converters, employing a state-space modelling approach for a comprehensive analysis. The study initiates with the establishment of a dynamic state-space representation, capturing the converters' behaviour under varying operational conditions. To understand steady-state features and transient responses, a comprehensive DC analysis is performed. Utilizing small-signal linearization techniques, the AC analysis leads to the derivation of the transfer function, revealing the system's frequency-dependent dynamics. The paper concludes with a meticulous stability assessment, employing established criteria to gauge the robustness of the DC-DC converters under diverse operating scenarios.

Keywords: *DC-DC Converters, State-Space Modelling, DC Analysis, AC Analysis, Duty Cycle, Transfer Function, Stability Inference.*

1. Introduction

DC-DC converters [1-2] are essential in power electronics for voltage regulation and energy transfer. This research employs advanced methodologies—state-space modeling, DC and AC analysis [3], transfer function derivation, and stability assessment—to comprehensively explore the dynamic [4] behavior of these converters [5]. The state-space [6] representation establishes a framework for in-depth analysis under varying operational conditions. The initial focus on DC analysis [7]-8] unveils steady-state and transient responses critical for practical implementation. Transitioning to the AC domain, small-signal linearization techniques yield the transfer function, incorporating the duty cycle as a significant parameter to reflect its impact on converter performance [9].

2. Proposed Converter Analysis

2.1. Negative Lift Converter (NLC)

Negative Output [10-11] Luo converters are relatively new DC-DC converters, used in voltage lift technique, is now used in the design of DC-DC converters [12], where the output voltage rises in arithmetic progression. It improves voltage transfer gain. The negative output Luo converter [13-14] gradually increases voltage transfer gain in a geometric progression with a simple structure [15]. Positive source voltage is converted to negative load voltage. In comparison to conventional DC-DC converters, it has higher voltage transfer gain, higher efficiency, and lower inductor current ripple. Figure 1 depicts the NLC circuit diagram.

The negative output Luo converter is made up of the following components: a DC supply source Vs, an inductor L, capacitors C1 and C2, freewheeling diodes D1, D2, an n-channel MOSFET switch S, and a load.

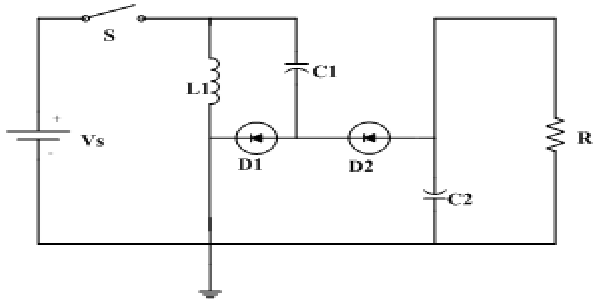

Fig.1 Negative Lift Converter-circuit diagram

2.2. Modes of Operation

In the modes of operation of NLC, the switch is assumed as ideal and NOLC operates in Continuous Conduction Mode (CCM). The MOSFET switch can be controlled to step up the input voltage. The NLC can be operated in two modes, depending upon whether the switch is ON or OFF

2.3. Interval I

The MOSFET switch is turned on during this interval. Figure 2 depicts the equivalent circuit for mode 1 operation. The current flowing through the inductor L1 increases during the ON time, while the capacitor C1 charged to Vs. During the ON period KT, the current flowing through the inductor increases with a slope of

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Vs/L1. The load discharges the capacitor C2. Switched models are identified over a switching cycle. The linear switched circuit model for each state of the switching converter is drawn (e.g., currents through inductors and voltages, across capacitors).

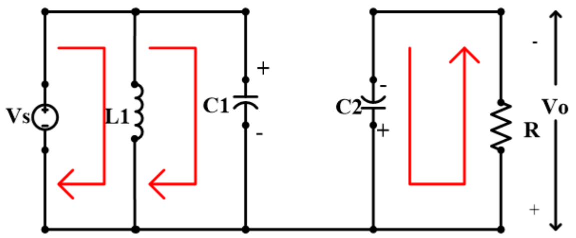

Fig. 2. Mode 1 Operation of NLC

2.4. Interval II

Figure 3 depicts the corresponding circuit of NLC in interval II. The MOSFET switch is turned off at interval II. The inductor current begins to fall with a slope of - (Vo-Vs)/L1. C1 discharges to the load, followed by C2.

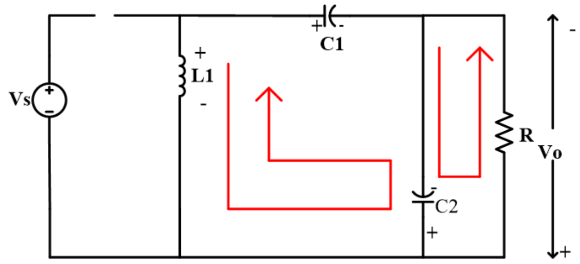

Fig. 3 Mode II Operation of NLC

The NLC is examined to find the inductor L, input capacitor C1, and output capacitor C2. The converter is analyzed in CCM mode to determine the above characteristics. During mode 1,

$$Vs = L\frac{di}{dt} \tag{a}$$

During Mode 2,

$$V_s - V_o = -L\frac{di}{dt} \tag{b}$$

The output voltage of the NOSLC is given by the following equation

$$V_o = \frac{V_s}{1-K} \tag{c}$$

It can also be written as

$$V_0 = \left(\frac{2-K}{1-k}\right)^n - 1*(V_s) \tag{d}$$

Where V_s is the supply voltage (V), $V_o V$ is the output voltage (V), K is the duty cycle (%).

2.5. Analysis of NLC with Its State Space Equations

For the state space analysis [16-17], let vC_1 be the voltage due to capacitor C1, vC_2 be the voltage due to capacitor C_2, iL_1 be the current due to inductor L1, i_o be the output current, V_{in} be the input voltage, v_0 is output voltage. State variables of the switching converter are identified and. state equations for each switched circuit model using Kirchhoff's voltage and current laws are written and portrayed in the following equations. The equations are formed from the on-off interval.

Let Vs = Vin and Vin can be written as,

$$Vin = L\frac{diL}{dt} \tag{1}$$

The current through the inductor L1 is given by,

$$C1\frac{dvc1}{dt} = iL1 \tag{2}$$

The output current in terms of load capacitor C2 and R is given by,

$$C2\frac{dvc2}{dt} = \frac{Vc2}{R} \tag{3}$$

The inductor voltage equation is given as,

$$L\frac{diL}{dt} = Vc2 - Vc1 \tag{4}$$

The capacitor current through C1 and C2 is given as,

$$iC1 = i0 - iL1 \tag{5}$$

$$iC2 = iL1 - io \tag{6}$$

The rate of change of inductor current is obtained by averaging equation (1) and (4)

$$\frac{di_L}{dt} = d_{\frac{v_{in}}{L}} + (1-d)\left(v_{\frac{C_2 - vC_1}{L}}\right) \tag{7}$$

The equation (7) is perturbed to yield steady-state (DC) and dynamic (AC) terms and eliminate the product of any AC terms. The perturbed equation (7a) is as follows,

$$\frac{d(i_L+\tilde{i_L})}{dt} = (D+\tilde{d})\frac{(V_{in}+\tilde{V_{in}})}{L} + (1-(D+\tilde{d}))\left(\left(\frac{vC_2+v\tilde{C}_2}{L}\right) - \left(\frac{vC_1+v\tilde{C}_1}{L}\right)\right) \tag{7a}$$

By averaging the equation (2) and (5), equation (8) is obtained as,

$$\frac{2\,di_L}{dt} - \frac{i_L}{C_1} + (1-d)\frac{i_o}{C_1} \tag{8}$$

The above equation is perturbed again to obtain the steady-state (DC) and dynamic (AC) terms and eliminate the product of any AC terms.

$$\frac{2(D+\tilde{d})(i_L+i\tilde{L})}{C_1} - \frac{(i_L+\tilde{i_L})}{C_1} + (1-(D+\tilde{d}))\left(\frac{i_o+\tilde{i_o}}{C_1}\right) \tag{8a}$$

The change in output voltage is obtained by the following equation (9) by averaging equation (3) and (6)

$$\frac{dv_{C_2}}{dt} = \frac{di_o}{C_2} + (1-d)\frac{i_L}{C_2} - (1-d)\frac{i_o}{C_2} \tag{9}$$

The above equation is perturbed again to obtain the steady-state (DC) and dynamic (AC) terms and eliminate the product of any AC terms.

$$\frac{d(v_{C_2}+v\tilde{C}_2)}{dt} = \frac{(D+\tilde{d})(i_o+\tilde{i_o})}{C_2} + (1-(D+\tilde{d}))\left(\frac{i_L+\tilde{i}_L}{C_2}\right) - \frac{(1-(D+\tilde{d})(i_o+\tilde{i_o}))}{C_2} \tag{9a}$$

Now, equation (7a) is rewritten, to carry out the DC and AC analysis.

$$\frac{di_L}{dt} + \frac{d\tilde{i_L}}{dt} = \frac{Dv_{in}}{L} + \frac{\tilde{D}v_{in}}{L} + \tilde{d}_{\frac{v\tilde{i}n}{L}} + \frac{\tilde{d}v_{in}}{L} + \frac{v\tilde{C_2}}{L} + \frac{vC_2}{L} - \frac{vC_1}{L} - \frac{v\tilde{C_1}}{L} - D_{\frac{vC_2}{L}} - \tilde{D}_{\frac{vC_2}{L}} + D_{\frac{vC_1}{L}} + \tilde{D}_{\frac{vC_1}{L}} - \tilde{d}_{\frac{vC_2}{L}} - \tilde{d}_{\frac{vC_1}{L}} + \tilde{d}_{\frac{vC_1}{L}} + \tilde{d}_{\frac{v\tilde{C_1}}{L}} \tag{10}$$

On DC analysis, equation (10) reveals that the output voltage modulation is due primarily to changes in the input voltage, $\acute{u}_1$ that is vin, the modulation in the duty cycle, d, and the modulation in the inductor current. From Equation (10), the steady-state or DC solution is obtained as,

$$Dv_{in} + vC_1\,(D-1) + vC_2\,(1-D) = 0 \quad (10a)$$

On AC analysis, equation (10), reveals that the steady-state input current is equal to the steady-state output voltage. The AC solution from Equation (10) is obtained as,

$$\frac{d\tilde{i_L}}{dt} = \frac{Dv_{in}}{L} + \frac{\tilde{D}v_{in}}{L} + \tilde{d}_{\frac{v\tilde{i}_n}{L}} + \frac{\tilde{d}v\tilde{i}_n}{L} + \frac{vC_2}{L} + \frac{v\widetilde{C_2}}{L} - \frac{vC_1}{L} - \frac{v\widetilde{C_1}}{L} - D_{\frac{vC_2}{L}} - \tilde{D}_{\frac{vC_2}{L}} + D_{\frac{vC_1}{L}} + \tilde{D}_{\frac{vC_1}{L}} - \tilde{d}_{\frac{vC_2}{L}} - \tilde{d}_{\frac{vC_1}{L}} + \tilde{d}_{\frac{vC_1}{L}} + \tilde{d}_{\frac{v\widetilde{C_1}}{L}} \quad (10b)$$

Equation 10(b) is further simplified to,

$$\frac{d\tilde{i_L}}{dt} = \frac{v_{in}}{L}\left(D + \tilde{d}\right) + \frac{\tilde{V_{in}}}{L}\left(D + \tilde{d}\right) + \frac{vC_2}{L}(1-D) + \frac{v\widetilde{C_2}}{L}(1-D) + \frac{vC_1}{L}(D-1) + \frac{v\widetilde{C_1}}{L}(D-1) + \frac{V\tilde{C_1}}{L}\left(\tilde{d}\right) + \frac{\tilde{d}V\tilde{C_1}}{L} - \tilde{d}_{\frac{vC_2}{L}} - \tilde{d}_{\frac{v\widetilde{C_2}}{L}} \quad (10c)$$

On taking DC term above equation is given by,

$$\frac{Dv_{in}}{L} + \frac{vC_1\,(D-1)}{L} + \frac{vC_2\,(1-D)}{L} = 0 \quad (10d)$$

Linear term for the above equation is given by,

$$\frac{\tilde{D}v_{in}}{L} + \tilde{d}_{\frac{v\tilde{i}_n}{L}} + \frac{v\widetilde{C_2}}{L} - \frac{v\widetilde{C_1}}{L} - \tilde{D}_{\frac{vC_2}{L}} + \tilde{D}_{\frac{vC_1}{L}} - \tilde{d}_{\frac{vC_2}{L}} + \tilde{d}_{\frac{vC_1}{L}}$$

$$D\frac{\tilde{v_{in}}}{L} + \tilde{d}_{\frac{v_{in}}{L}} + \frac{v\tilde{C_1}}{L}(D-1) + \frac{v\tilde{C_2}}{L}(1-D) - \tilde{d}_{\frac{vC_2}{L}} + \tilde{d}_{\frac{vC_1}{L}} \quad (10e)$$

These equations result in a set of nonlinear continuous equations. A nonlinear continuous equivalent circuit can be drawn from this set of nonlinear equation

Non-Linear term for the above equation is given by,

$$\frac{\tilde{d}V\tilde{i}_n}{L} - \frac{\tilde{d}v\tilde{C}_2}{L} + \frac{\tilde{d}v\tilde{C}_1}{L} \quad (10f)$$

Neglecting DC and Non-linear term from equation (10c), linear term equation (10g) is obtained as,

$$\frac{d\tilde{i}_L}{dt} = D\frac{v\tilde{i}_n}{L} + d\frac{\tilde{v}_{in}}{L} + \frac{v\tilde{C}_1}{L}(D-1) + \frac{v\tilde{C}_2}{L}(1-D) - \tilde{d}_{\frac{vC_2}{L}} + \tilde{d}_{\frac{vC_1}{L}} \quad (10g)$$

The output voltage can be written in terms of state equation terms C and B. It is given as follows,

$$\tilde{v}_0 = \tilde{C}\left(SI - \tilde{A}\right)^{-1}\tilde{B}\tilde{v}_{in} \quad (10h$$

AC analysis is carried out in equation (8) and it is rewritten as,

$$\frac{2Di_L}{C_1} + \frac{2\tilde{d}i_L}{C_1} + \frac{2\tilde{D}i_L}{C_1} + \frac{2\tilde{d}\tilde{i_L}}{C_1} - \frac{i_L}{C_1} - \frac{\tilde{i}_L}{C_1} + \frac{i_0}{C_1} + \frac{\tilde{i}_0}{C_1} - \frac{Di_0}{C_1} - D\frac{\tilde{i}_0}{C_1} - \frac{d\tilde{i}_0}{C_1} - \frac{\tilde{d}i_0}{C_1} \quad (11)$$

Neglecting DC and Non-linear terms the equation (8) becomes, taking only linear term,

$$\frac{2\,d\tilde{i_L}}{C_1} + \frac{2\tilde{D}_{iL}}{C_1} + \frac{\tilde{i}_0}{C_1} - \frac{\tilde{i}_L}{C_1} - \frac{D\tilde{i}_0}{C_1} - \frac{d\tilde{i}_0}{C_1}s \quad (11a)$$

In the same way, equation (9) is rewritten as,

$$\frac{dvC_2}{dt} = \frac{di_0}{C_2} + (1-d)\frac{i_L}{C_2} - (1-d)\frac{i_0}{C_2}$$

$$\frac{dvC_2}{dt} = \frac{di_0}{C_2} + (1-d)\frac{i_L}{C_2} - (1-d)\frac{i_0}{C_2} - \frac{d\left(v_{C_2} + v\tilde{C}_2\right)}{dt} = \frac{(D+\tilde{d})(i_0+\tilde{i}_0)}{C_2} + \left(1-\left(D+\tilde{d}\right)\right)\left(\frac{i_L+\tilde{i}_L}{C_2}\right) - \frac{\left(1-(D+\tilde{d})(i_0+\tilde{i}_0)\right)}{C_2} \quad (12)$$

Equation (12) is further simplified to,

$$\frac{dv_{C_2}}{dt} + \frac{d\tilde{v}C_2}{dt} = \frac{Di_0}{C_2} + D\frac{\tilde{i}_0}{C_2} + \frac{d\tilde{i}_0}{C_2} + \frac{\tilde{d}i_0}{C_2} + \frac{i_L}{C_2} + \frac{\tilde{i}_L}{C_2} - \frac{Di_L}{C_2} - \frac{\tilde{D}i_L}{C_2} - \frac{\tilde{d}i_L}{C_2} - \frac{\tilde{d}i_L}{C_2} - \frac{i_0}{C_1} + \frac{\tilde{i}_0}{C_1} \quad (12a)$$

DC analysis for equation (9) is given as lysis for equation (9) is given as,

$$0 = \frac{Di_0}{C_2} + \frac{i_L}{C_2} - D\frac{i_L}{C_2} - \frac{i_0}{C_2}, Di_0 + i_L - Di_L - i_0 = 0, D(i_0 - i_L) + \left(i_L - \dot{I}_0\right) = 0 \quad (12b)$$

On AC analysis equation (9) is given by

$$\frac{dVC_2}{dt} = \frac{i_0}{C_2}\left(D + \tilde{d}\right) + \frac{\tilde{i}_0}{C_2}\left(D + \tilde{d}\right) + \frac{i_L}{C_2}(1-D) - \frac{i_0}{C_2} - \frac{\tilde{i}_0}{C_2} - \frac{\tilde{d}I_L}{C_2} - \frac{\tilde{d}\tilde{i}_L}{C_2} \quad (12c)$$

On taking DC term alone, the above equation becomes,

$$D(i_0 - i_L)/C_2 + \left(i_L - \dot{I}_0\right)/C_2 = 0 \quad (12d)$$

Linear terms are taken from the above equation and given as,

$$\frac{Di_0}{C_2} + \frac{di_0}{C_2} + \frac{i_L}{C_2} - \frac{Di_L}{C_2} - \frac{di_L}{C_2} - \frac{i_0}{C_2} = 0$$

$$\frac{i_0}{C_2}(D-1) + \frac{\tilde{i_L}}{C_2}(1-D) + \frac{\tilde{d}i_0}{C_2} - \frac{\tilde{d}i_L}{C_2} \quad (12e)$$

Non-Linear term for the above equation is given by,

$$\frac{\partial i_o}{C_2} - \frac{\partial i_L}{C_2} \quad (12f)$$

Neglect DC and Non-linear term then equation (9) becomes, i.e, taking only linear term,

$$\frac{\partial \widetilde{vc_2}}{C_2} - \frac{i_o}{C_2}(D-1) + \frac{i_L}{C_2}(1-D) + \frac{\partial i_o}{C_2} - \frac{\partial i_L}{C_2} \quad (12g)$$

Hence the linear terms derived from equation (7), equation (8), equation (9) is given by,

$$D\frac{\tilde{V}_{in}}{L} + \frac{\tilde{d}V_{in}}{L} + \frac{\widetilde{Vc_1}}{L}(D-1) + \frac{V\tilde{c}_2}{L}(1-D) - \frac{\tilde{d}Vc_2}{L} + \frac{\tilde{d}Vc_1}{L} \quad (13)$$

$$2\,\frac{\tilde{d}i_L}{C_1} + 2\frac{Di_L}{C_1} + \frac{\tilde{i_0}}{C_1} - \frac{\tilde{i_L}}{C_1} - \frac{D\tilde{i}_0}{C_1} - \frac{d\tilde{i}_0}{C_1} \quad (14)$$

$$\frac{i_0}{C_2}(D-1) + \frac{i_1}{C_2}(1-D) + \frac{\tilde{d}i_0}{C_2} - \frac{\tilde{d}i_L}{C_2} \quad (15)$$

The above equations are converted to matrix form, and obtained as,

$$\begin{pmatrix} \frac{d\tilde{i_1}}{dt} \\ \frac{d\widetilde{vc_1}}{dt} \\ \frac{d\widetilde{vc_2}}{dt} \end{pmatrix} = \begin{pmatrix} 0 & \frac{(D-1)}{L} & \frac{(1-D)}{L} \\ \frac{(2D-1)}{c_1} & 0 & 0 \\ \frac{(1-D)}{c_2} & 0 & 0 \end{pmatrix} \begin{pmatrix} \tilde{i_L} \\ \widetilde{vc_1} \\ \widetilde{vc_2} \end{pmatrix} + \begin{pmatrix} \frac{D}{L} \\ 0 \\ 0 \end{pmatrix} \widetilde{v_{in}} +$$

$$\begin{pmatrix} \frac{vc_1 - vc_2}{L} \\ 2\frac{i_L - i_0}{c_1} \\ \frac{i_0 - i_L}{c_2} \end{pmatrix} \times \begin{pmatrix} \frac{D}{L} \\ 0 \\ 0 \end{pmatrix} \widetilde{v_{in}} + \begin{pmatrix} \frac{vc_1 - vc_2}{L} \\ 2\frac{i_L - i_0}{c_1} \\ \frac{i_0 - i_L}{c_2} \end{pmatrix} \times \begin{pmatrix} \frac{d\tilde{i_1}}{dt} \\ \frac{d\tilde{vc_1}}{dt} \\ \frac{d\tilde{vc_2}}{dt} \end{pmatrix} =$$

$$[0 \quad 0 \quad 1] \begin{pmatrix} i_L \\ vc_1 \\ vc_2 \end{pmatrix} \tag{16}$$

Thus A, B, and C are derived from (16).

$$A = \begin{pmatrix} 0 & \frac{(D-1)}{L} & \frac{(1-D)}{L} \\ \frac{(2D-1)}{c_1} & 0 & 0 \\ \frac{(1-D)}{c_2} & 0 & 0 \end{pmatrix}, B = \begin{pmatrix} \frac{D}{L} \\ 0 \\ 0 \end{pmatrix}, C = [0\ 0\ 1] \tag{17}$$

The $\tilde{V}_0$namely the output voltage is given by,

$$\tilde{V}_0 = \tilde{C}(SI - \tilde{A})^{-1}\tilde{B}\widetilde{V_{in}} \tag{18}$$

of the matrix is to be obtained

$$SI = \begin{bmatrix} S & 0 & 0 \\ 0 & S & 0 \\ 0 & 0 & S \end{bmatrix};$$

$$(SI - A) = \begin{pmatrix} S & -\frac{(D-1)}{L} & -\frac{(1-D)}{L} \\ -\frac{(2D-1)}{c_1} & S & 0 \\ -\frac{(1-D)}{c_2} & 0 & S \end{pmatrix}$$

$$(\mathrm{SI} - \mathrm{A})^{-1} = \frac{1}{|\mathrm{SI} - \mathrm{A}|}\mathrm{adj}(\mathrm{SI} - \mathrm{A})$$

$$|\mathrm{SI} - \mathrm{A}| = S(s^2) + \frac{(D-1)}{L} * \frac{(2D-1)}{c_1} \times (-s) + \frac{(1-D)}{L} \times \frac{(D-1)}{L}$$

$$= s^3 + s\frac{(1-D)^2}{Lc_1} - s\frac{(2D-1)}{c_1}\frac{(D-1)}{L}$$

$$adj(SI - A) = cofac(SI - A)^T$$

To find the adjoint, the cofactor for the matrix is performed,

$$\mathrm{cofac}(\mathrm{SI} - \mathrm{A}) = \begin{pmatrix} s^2 & s\frac{(2D-1)}{c_1} & -s\frac{(1-D)}{c_2} \\ s\frac{(D-1)}{L} & s^2 + \frac{(1-D)^2}{Lc_2} & \frac{(D-1)^2}{Lc_2} \\ -s\frac{(1-D)}{L} & -\frac{(1-D)(2D-1)}{Lc_1} & s^2 + \frac{(D-1)(2D-1)}{Lc_1} \end{pmatrix}$$

$$\mathrm{adj}(\mathrm{SI} - \mathrm{A}) = \begin{pmatrix} s^2 & s\frac{(D-1)}{L} & -s\frac{(1-D)}{L} \\ s\frac{(2D-1)}{c_1} & s^2 + \frac{(1-D)^2}{Lc_2} & -\frac{(1-D)(2D-1)}{Lc_1} \\ -s\frac{(1-D)}{c_2} & \frac{(D-1)^2}{Lc_2} & s^2 + \frac{(D-1)(2D-1)}{Lc_1} \end{pmatrix}$$

$$(\mathrm{SIS1} - \mathrm{A})^{-1} \frac{1}{(s^3 + \frac{s(1-D)^2}{Lc_2} - \frac{s(D-1)(2D-1)}{Lc_1}} \times \begin{pmatrix} s^2 & s\frac{(D-1)}{L} & -s\frac{(1-D)}{L} \\ s\frac{(2D-1)}{c_1} & s^2 + \frac{(1-D)^2}{Lc_2} & -\frac{(1-D)(2D-1)}{Lc_1} \\ -s\frac{(1-D)}{c_2} & \frac{(D-1)^2}{Lc_2} & s^2 + \frac{(D-1)(2D-1)}{Lc_1} \end{pmatrix}$$

$$v_o = \frac{[0\ 0\ 1]}{(s^3 + \frac{s(1-D)^2}{Lc_2} - \frac{s(D-1)(2D-1)}{Lc_1}} \times \begin{pmatrix} s^2 & s\frac{(D-1)}{L} & -s\frac{(1-D)}{L} \\ s\frac{(2D-1)}{c_1} & s^2 + \frac{(1-D)^2}{Lc_2} & -\frac{(1-D)(2D-1)}{Lc_1} \\ -s\frac{(1-D)}{c_2} & \frac{(D-1)^2}{Lc_2} & s^2 + \frac{(D-1)(2D-1)}{Lc_1} \end{pmatrix}$$

$$v_o = \frac{[0\ 0\ 1]}{(s^3 + \frac{s(1-D)^2}{Lc_2} - \frac{s(D-1)(2D-1)}{Lc_1}} \times \begin{pmatrix} s^2 & s\frac{(D-1)}{L} & -s\frac{(1-D)}{L} \\ s\frac{(2D-1)}{c_1} & s^2 + \frac{(1-D)^2}{Lc_2} & -\frac{(1-D)(2D-1)}{Lc_1} \\ -s\frac{(1-D)}{c_2} & \frac{(D-1)^2}{Lc_2} & s^2 + \frac{(D-1)(2D-1)}{Lc_1} \end{pmatrix} \begin{pmatrix} \frac{D}{L} \\ 0 \\ 0 \end{pmatrix} v_{in}$$

2.6 Transfer Function

The transfer function of a system is the ratio of Laplace transform of output to the Laplace transform of input where all the initial conditions are zero, hence the transfer function is obtained as,

$$\frac{v_0}{v_{in}} = \frac{[0\ 0\ 1]}{(s^3 + \frac{s(1-D)^2}{Lc_2} - \frac{s(D-1)(2D-1)}{Lc_1}}$$

$$\begin{pmatrix} s^2 & s\frac{(D-1)}{L} & -s\frac{(1-D)}{L} \\ s\frac{(2D-1)}{c_1} & s^2 + \frac{(1-D)^2}{Lc_2} & -\frac{(1-D)(2D-1)}{Lc_1} \\ -s\frac{(1-D)}{c_2} & \frac{(D-1)^2}{Lc_2} & s^2 + \frac{(D-1)(2D-1)}{Lc_1} \end{pmatrix} \begin{pmatrix} \frac{D}{L} \\ 0 \\ 0 \end{pmatrix}$$

$$[0 \quad 0 \quad 1] \begin{bmatrix} s^2 & \frac{S(D-1)}{L} & -\frac{S(1-D)}{L} \\ S\left(\frac{2D-1}{C_1}\right) & S^2\frac{(1-D)^2}{LC_2} & -\frac{(1-D)(2D-1)}{LC_1} \\ -S\left(\frac{1-D}{C_2}\right) & \left(\frac{(D-1)^2}{LC^2}\right) & S^2 + \frac{(D-1)(2D-1)}{LC_1} \end{bmatrix}$$

$$\left[-S\left(\frac{1-D}{C_2}\right) \quad \frac{(D-1)^2}{LC^2} \quad S^2 + \frac{(D-1)(2D-1)}{LC_1}\right] \begin{bmatrix} \frac{D}{L} \\ 0 \\ 0 \end{bmatrix} - \frac{DS}{L}\left(\frac{1-D}{C_2}\right)$$

Hence, we get transfer function as,

$$\frac{V_0}{V_{IN}} \Rightarrow \frac{t}{f} = \frac{-\frac{DS}{L}(\frac{1-D}{C_2})}{S^3 + S\frac{(1-D)^2}{LC_2} - \frac{S(D-1)(2D-1)}{LC_1}} \tag{19}$$

$$TF => \frac{-\frac{DS}{L}\left(\frac{1-D}{C_2}\right)}{S^3 + S\frac{(1-D)^2}{LC_2} - \frac{(D-1)(2D-1)}{LC_1}}$$

$$G(s)L_1(s) = 0$$

$$\Rightarrow 1 + \frac{\frac{-Ds}{L}\left(\frac{1-D}{C_2}\right)}{sin^3\, s(\frac{(1-D)^2}{LC_2} - \frac{(D-1)(2D-1)}{LC_1})} = 0$$

$$S^3 + S\left(\frac{(1-D)^2}{LC_2} - \frac{(D-1)(2D-1)}{LC_1}\right)\frac{-\ DS}{L}\left(\frac{(1-D)}{C_2}\right) = 0$$

$$S^3 + \frac{S(1-D)^2}{LC_2} - \frac{(D-1)(2D-1)}{LC_1} - \frac{DS}{L}\frac{(1-D)}{C_2} = 0$$

$$S^3 + \frac{S[1-D^2-2D]}{LC_2} - \frac{S(2D^2-D-2D+1)}{LC_1} - \frac{DS}{LC_2} + \frac{D^2S}{LC_2} = 0$$

$$S^3 + \frac{S}{LC_2} + \frac{D^2S}{LC_2} - \frac{2DS}{LC_2} - \frac{2SR^2}{LC_1} + \frac{SD}{LC_1} + \frac{2DS}{LC_1} - \frac{S}{LC_1} - \frac{DS}{LC_2} + \frac{D^2S}{LC_2} = 0$$

$$S^3 + \frac{2D^2S}{LC_2} - \frac{3DS}{LC_2} + \frac{S}{LC_2} - \frac{S}{LC_1} + \frac{3DS}{LC_1} - \frac{2D^2S}{LC_1} = 0$$

$$S^3 + 2D^2S\left(\frac{1}{LC_2} - \frac{1}{LC_1}\right) + 3DS\left[\frac{1}{LC_1} - \frac{1}{LC_2}\right] + S\left[\frac{1}{LC_2} - \frac{1}{LC_1}\right] = 0$$

$$S^3 + S\left[2D^2\left(\frac{1}{LC_2} - \frac{1}{LC_1}\right) + 3D\left(\frac{1}{LC_1} - \frac{1}{LC_2}\right) + \left(\frac{1}{LC_2} - \frac{1}{LC_1}\right)\right] = 0 \tag{20}$$

Thus, a third order equation is obtained as a transfer function for the given circuit, as the number of charging elements present in the circuit is 3 and hence it satisfied the relation of order. The output voltage change with respect to duty cycle can also be derived in the following equations.

$$v_0 = c(\widetilde{SI - \widetilde{A}})$$

$$(SI - \widetilde{A})^{-1} = \frac{1}{(s^3 + \frac{s(1-D)^2}{Lc_2} - \frac{s(D-1)(2D-1)}{Lc_1}}$$

$$\begin{pmatrix} s^2 & s\frac{(D-1)}{L} & -s\frac{(1-D)}{L} \\ s\frac{(2D-1)}{c_1} & s^2 + \frac{(1-D)^2}{Lc_2} & -\frac{(1-D)(2D-1)}{Lc_1} \\ -s\frac{(1-D)}{c_2} & \frac{(D-1)^2}{Lc_2} & s^2 + \frac{(D-1)(2D-1)}{Lc_1} \end{pmatrix}$$

$$\frac{v_o}{\partial} = \frac{[\,0\ 0\ 1\,]}{(s^3 + \frac{s(1-D)^2}{Lc_2} - \frac{s(D-1)(2D-1)}{Lc_1}}$$

$$\begin{pmatrix} s^2 & s\frac{(D-1)}{L} & -s\frac{(1-D)}{L} \\ s\frac{(2D-1)}{c_1} & s^2 + \frac{(1-D)^2}{Lc_2} & -\frac{(1-D)(2D-1)}{Lc_1} \\ -s\frac{(1-D)}{c_2} & \frac{(D-1)^2}{Lc_2} & s^2 + \frac{(D-1)(2D-1)}{Lc_1} \end{pmatrix}$$

$$=\frac{v_o}{\partial} =$$

$$\frac{[\,0\ 0\ 1\,]}{(s^3 + \frac{s(1-D)^2}{Lc_2} - \frac{s(D-1)(2D-1)}{Lc_1}} \begin{pmatrix} s^2 & s\frac{(D-1)}{L} & -s\frac{(1-D)}{L} \\ s\frac{(2D-1)}{c_1} & s^2 + \frac{(1-D)^2}{Lc_2} & -\frac{(1-D)(2D-1)}{Lc_1} \\ -s\frac{(1-D)}{c_2} & \frac{(D-1)^2}{Lc_2} & s^2 + \frac{(D-1)(2D-1)}{Lc_1} \end{pmatrix}$$

$$= \frac{[s\frac{(1-D)}{c_2}\frac{(D-1)^2}{Lc_2}s^2 + \frac{(D-1)(2D-1)}{Lc_1}]}{(s^3 + \frac{s(1-D)^2}{Lc_2} - \frac{s(D-1)(2D-1)}{Lc_1}} \begin{pmatrix} \frac{D}{L} \\ 0 \\ 0 \end{pmatrix}$$

As a result, the duty cycle transfer function is given by,

$$\frac{v_0}{\tilde{d}} = \frac{\frac{(1-D)DS}{Lc_2}}{(s^3 + \frac{s(1-D)^2}{Lc_2} - \frac{s(D-1)(2D-1)}{Lc_1}} \tag{21}$$

In addressing stability, responsiveness, and accuracy issues in an open-loop control system, compensation becomes crucial when altering system parameters is impractical due to real-world constraints.

Compensatory elements, often economically added, modify the transfer function to enhance performance. Designing a compensator, achieved through root locus or frequency response plots, aims to make the system stable with desirable transient response and minimal steady-state errors. Compensation methods include integral for steady-state error elimination, proportional-integral (PI) for stability with transient responsiveness, and proportional-derivative (PD) for improving transient response in accurate yet unstable systems. Controller adjustments, using root locus or Bode plots, can be implemented in parallel or series with the plant to optimize system performance without altering plant characteristics.

For the given transfer function equation, Routh Hurwitz criterion method is verified.

$$S^3\,1\ \left[2D^2\left(\frac{1}{LC_2} - \frac{1}{LC_1}\right) + 3D\left(\frac{1}{LC_1} - \frac{1}{LC_2}\right) + \left(\frac{1}{LC_2} - \frac{1}{LC_1}\right)\ \right]$$

$$[S^2\quad 0\quad 0]$$

$$[S^2\quad 3S^2]\left[2D^2\left(\frac{1}{LC_2} - \frac{1}{LC_1}\right) + 3D\left(\frac{1}{LC_1} - \frac{1}{LC_2}\right) + \left(\frac{1}{LC_2} - \frac{1}{LC_1}\right)\right]$$

$$\frac{2D^2\left(\frac{1}{LC_2} - \frac{1}{LC_1}\right) + 3D\left(\frac{1}{LC_1} - \frac{1}{LC_2}\right) + \left(\frac{1}{LC_2} - \frac{1}{LC_1}\right) - 3S^2\left[2D^2\left(\frac{1}{LC_2} - \frac{1}{LC_1}\right) + 3D\left(\frac{1}{LC_1} - \frac{1}{LC_2}\right) + \left(\frac{1}{LC_2} - \frac{1}{LC_1}\right)\right]}{3S^2}$$

$$S^0\ -\left[2D^2\left(\frac{1}{LC_2} - \frac{1}{LC_1}\right) + 3\mathrm{D}\left(\frac{1}{LC_1} - \frac{1}{LC_2}\right) + \left(\frac{1}{LC_2} - \frac{1}{LC_1}\right)\right]$$

In electrical terms, a sign change in the Routh array [18] suggests the existence of poles with positive real parts and this can be interpreted as an indication of instability in the electrical system. In practical terms, an unstable system can lead to undesirable analysis [19-22], oscillations, or even failure in certain cases.

2.7 Conclusion:

In summary, the research employs state-space modelling to analyse the dynamic behaviour of DC-DC converters. The stability analysis utilizes the Routh-Hurwitz criterion applied to the characteristic equation derived from the state-space representation. With a single sign change indicating one pole in the right-half plane, the converters are classified as unstable. This approach offers a thorough and professional exploration of the converters' behaviour, essential for advancing power electronics and voltage regulation.

Author contributions

Name1 Surname1: Conceptualization, Methodology, y**Name2 Surname2:** Data curation, Writing-Original draft preparation, Validation., Field study **Name3 Surname3and 4:** Visualization, Investigation, Writing-Reviewing and Editing.

References

[1] Vinayagam, C., (2016). Comparative Analysis of Analog and Digital Controllers for Negative Output Superlift Luo Converter (NOSLC). Circuits and Systems, 7(8), 1689-1700. DOI: 10.4236/cs.2016.78146.

[2] Luo, F. L., Ye, H., Rashid, M. H., (2002). Super-lift Luo-converters. Power Electronics Specialists Conference, 2002. pesc 02. 2002 IEEE 33rd Annual, 2, 10.1109/PSEC.2002.1022490.2nd ed., vol. 3, J . Peters, E d . New Y o r k , NY, USA: McGraw-Hill,1964,pp.15–64.

[3] . Ghafour, Z. A., Ahmed, R., Yasin, N. M., Noaman, N. M., (2023). Efficient Design, Analysis and Implementation of Super-Lift LUO Converter for Standalone PV Applications. Journal of Techniques, 5(2), 81-88.

[4] 4. Chamundeeswari, V., Seyezhai, R., (2013). Dynamic analysis and parameter evaluation of negative output superlift luo converter. Publication date 2013.

[5] Madhappan, C., Babu, M. R., Sujatha, R., (2014). Design And Simulation of LUO Converter Topologies For Photovoltaic Applications. International Journal of Applied Engineering Research, 9(23), 21553-21560.

[6] Shenoy, K. L., Nayak, C. G., Mandi, R. P., (2017). State space analysis of boost DC/DC converter with voltage mode control. Volume 1859, Issue 1, 19 July, 1-8.

[7] Vinayagam, C., Seyezhai, R., (2016). Comparative Analysis of Analog and Digital Controllers for Negative Output Superlift Luo Converter (NOSLC). Circuits and Systems, 07(08), 1689-1700. DOI: 10.4236/cs.2016.78146.

[8] Luo, F. L., He, Y., (2005). Analysis of Luo converters with voltage-lift circuit. IEE Proceedings - Electric Power Applications, 152(5), 1239-1252. DOI: 10.1049/ip-epa:20045176.

[9] Palani, A., Venmathi, M., Vijayaragavan, M., Vengadakrishnan, K., (2022). Performance Enhancement of Grid Integrated Photovoltaic System Using Luo Converter. IEEE Canadian Journal of Electrical and Computer Engineering.

[10] Chamundeeswari, V., Seyezhai, R., (2014). Digital control for Negative Output Superlift Luo Converter using ARM Processor. International conference on Emerging Electrical systems and control.

[11] Luo, F. L., (1999). Negative output Luo converters: Voltage lift technique. IEE Proceedings - Electric Power Applications, 146(2), 208-224. DOI: 10.1049/ip-epa:19990302.

[12] Luo, F. L., (1998). Luo-converters voltage lift technique. Power Electronics Specialists Conference, 1998. PESC 98 Record. Annual IEEE, 2. DOI: 10.1109/PESC.1998.703423.

[13] 13. Luo, F. L., (1997). Luo-Converters, a series of new DC-DC step-up (boost) conversion circuits. Power Electronics and Drive Systems, 1997 International Conference on, Proceedings., 2. DOI: 10.1109/PEDS.1997.627511.

[14] Luo, F. L., Ye, H., (2003). Negative output super-lift Luo-Converters. PESC Record - IEEE Annual Power Electronics Specialists Conference, 18(5), 1361-1366 (Vol. 3).

[15] Tan, R. H. G., Hoo, L. Y. H., (2015). DC-DC converter modeling and simulation using state space approach. 2015 IEEE Conference on Energy Conversion (CENCON).

[16] Ibrahim, O., Yahaya, N. Z., Saad, N., (2016). State-space Modelling and Digital Controller Design for DC-DC Converter. TELKOMNIKA, 14(2), 497–506.

[17] Shera, E., (Year). State-Space "Switching" Model of DC-DC Converters in SystemVerilog. Methodology, Nabern, Germany: Dialog Semiconductor.

[18] Wang, S. G. (2019). New Routh-Type Table Method for Stability Test of Polynomials and Their Systems. 2019 Chinese Control Conference (CCC), July 2019.

[19] Moutabir, A., Abouloifa, A., Abdelmounim, E., Aboulfatah, M., Majdoul, R., & Touati, A. (2014). Analysis and control design of two cascaded boost converter. Web of Conferences, 60(2014), 201. DOI: 10.1051/conf/20140602001

[20] Chamundeeswari, V., Seyezhai, R., Robin, A. A., (2012). Stabilization and Robustification of negative output superlift luo converter using sliding mode control approach. Vol. 3, Issue 2, 508-519.

[21] ahu, B. K., Gupta, M. M., & Subudhi, B. (2013). Stability analysis of nonlinear systems using dynamic-Routh's stability criterion: A new approach. Advances in Computing, Communications and Informatics (ICACCI), 2013 International Conference on, DOI:10.1109/ICACCI.2013.6637448.

[22] Bologna, E., Deseri, L., & Zingales, M. (Year). A state-space approach to dynamic stability of fractional-order systems: The extended Routh-Hurwitz theorem.