Journal of Engineering Education Transformations ,
Volume 35 , No. 4 , April 2022 , ISSN 2349-2473, eISSN 2394-1707

Educational aid for dynamic study of DC converter with Leverrier's and Pole clustering technique using simulation software

Divya Navamani[1], Rishab Mrinal[2], Lavanya A[3], Geetha A[4]
[1]divyateddy1@gmail.com
[2]mrinalrishabh.2143@gmail.com
[3]lavanyaa@srmist.edu.in
[4]geethaa2@srmist.edu.in

Abstract : In this paper, the dynamic analysis of the dc-dc converter is proposed with an educational aid to ease the process in which the study is carried out. This study's primary importance is that it can be added to the curriculum of Master's program in Electrical Engineering. This article mainly focuses on the mathematical modelling of the dc-dc converter with which the dynamic analysis is carried out to regulate the load and line condition. The main problems in the analysis of higher-order dc-dc converter is addressed with techniques available in the literature. A quadratic boost converter with DCL cell is chosen for studying the dynamic analysis with the flow of the technique proposed. The solution to the resolvent matrix of the converter is obtained using Leverrier's algorithm. The higher-order system's transfer function is reduced using the pole clustering technique to ease the controller design. Finally, the PI controller is tuned with Ziegler-Nichols tuning and it is incorporated with the converter using the reduced-order transfer function. The input to output transfer function is analyzed with the step response in MATLAB software and compared with the full order transfer function to validate the reduced-order transfer function. The closed-loop response is also validated both with full order and reduced-order system.

Divya Navamani
divyateddy1@gmail.com

Keywords : Bloom's taxonomy, Leverrier's algorithm, Pole clustering, DC-DC converter, dynamic, reduced-order, controller

1. Introduction

In 1956, Benjamin Bloom, a psychologist, had recommended Bloom's taxonomy (learning objectives) for educators. It has recently been updated with six levels of learning that can be used to frame the learning objectives for any course. Bloom's taxonomy levels are remembering, understanding, applying, analysing, evaluating, and creating (RUA2EC). It is also observed that Bloom's taxonomy intrudes in the assessment process [1] and in framing the curriculum for bachelor's and master's programs. Many articles are recently published on the correlation of Bloom's taxonomy with many undergraduate courses [2]. Fig 1 reveals the latest levels of Bloom's taxonomy. Mostly, many countries follow this level for upgrading the teaching-learning methodology.

According to Bloom's taxonomy, the sixth level is creating a novel or innovative work on its own. To meet out this learning objective, the study should be

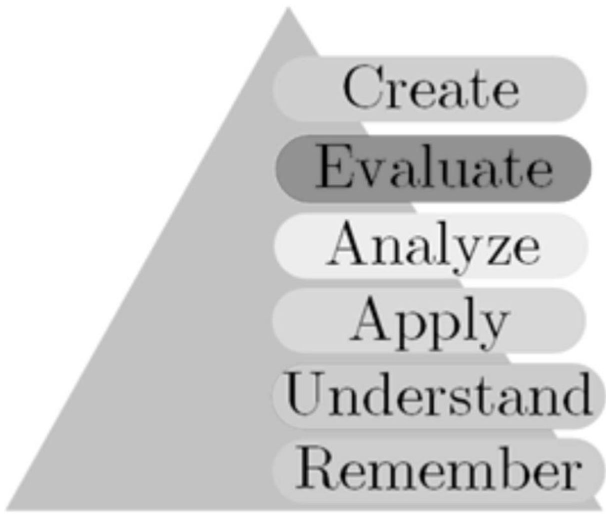


Fig. 1: Six levels of Bloom's taxonomy

exposed to design, develop, construct, assemble, and investigate. To develop a model, students should be in a position to create the entire system.

Postgraduate students who are interested in fetching degree on power electronics and industrial drives are needed to learn the courses like

- Analysis of power converters
- Modelling of power converters
- Power electronics converters in a renewable energy system
- Power converters in solid-state DC and AC drives
- Design of controller for power electronic applications.

To ease the mathematical analysis of power converters for all the above courses, this paper has introduced a simple algorithm for performing a dynamic analysis of power converters. The algorithm is explained with a flowchart and an illustrative example for better understanding.

Fig 2 depicts the process involved in the proposed methodology to study the dynamic analysis of the converter. It is a four-step process where four techniques are integrated to analyze the performance of the converter. All these techniques were used earlier for several analyses. However, this is the first time

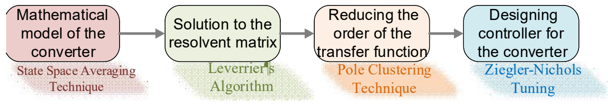


Fig. 2: Process to carry out dynamic analysis

these techniques are combined and suggested a methodology to study the dc-dc converter.

To perform dynamic analysis on power converters, many modeling techniques are incorporated [3-10]. In the last four decades, model reduction techniques attracted many researchers to design and model the system. They are several frequency and time-domain model reduction techniques. Frequency-domain techniques such as pole clustering, Pade approximation, Routh approximation, and Routh stability are mostly used to reduce the order of the dc-dc converter's transfer function [11-15]. Pole clustering is observed to be simple in calculating the numerator and denominator of the reduced-order model. Hence, it is chosen and adopted for this methodology. Finally, the controller is designed for the topology to meet the required design needs.

For many industrial applications, the PID controller is deployed. PID controller is employed for a didactic thermal plant in an Arduino platform [16]. In this controller, the tuning parameters are obtained with step response-based Ziegler-Nichol's method. A novel method of tuning is proposed for the PID controller, which unifies the Ziegler-Nichols method [17]. For the magnetic levitation system, the fractional-order PID controller's controller parameters are tuned by the Ziegler-Nichols method and ant colony optimization algorithm [18]. Ziegler-Nichol's method is also used for pneumatic soft robot control systems adjusted manually and automatically [19].

PI controllers are also used for various power converters to implement several control strategies for many applications. The isolated phase-shifted full-bridge dc-dc converter is proposed for a hybrid electric vehicle with particle swarm optimization where the PI controller is tuned with the Ziegler-Nichols method [20]. Ziegler – Nichol's method is also known as the critical proportionality method, which is a widely used heuristic parameter adjusting technique. The precise steps are to detach the differential and integral links, set the scale to a small value, fix the converter in closed-loop operation, and steadily increase the regulator's scale Kp to attain

Fig. 3: Step-by-step procedure for this methodology

critical oscillation progression. The gain is called ultimate gain, and the time between two peaks is called critical or ultimate oscillation period. Ziegler – Nichol's method proposes two tuning ways [21], one based on step response and another on frequency response experiment. In this paper, the frequency response method has been followed. This method produces good initial Kp, Ki , Kd value. This method remains the most straightforward technique from the tuning point of view.

Fig 3 depicts the step-by-step procedure involved for this pilot study. This paper deals with the mathematical modelling of the power converter (dc-dc converter) and designing a suitable controller for the proposed dc-dc converter. Recent educational tools for the design of power converters are elaborated in section 2. Section 3 describes the mathematical modelling of derived topology. Section 4 describes the simplified method and its application to the topology for solving the resolvent matrix. Bringing down the transfer function's order is to ease the controller's design for a power converter and is discussed in section 5. A suitable controller is suggested for the derived topology in simplified form is presented in section 6. The discussed algorithm is validated with an example in section 7. Section 8 presents the experimental results of the pilot study carried out. Finally, the results are validated in section 9.

2. Recent And Modern Educational Tool For Power Electronic Design

Several simulation packages are available for students and researchers for design of novel power electronic converter topologies. These softwares can also be used as a teaching tool for undergraduate and postgraduate students to understand the operating principle of the existing converters in literature. In these packages, few softwares are open-source or the trail/demo versions are available for the study. In our institution, SRM institute of Science and Technology, there are around six softwares exclusively for power converters. Fig 4 presents the software more commonly used for power electronic converter design and analysis.

Various hardware components for power electronics are also available to enhance the teaching methodology and to increase the interest in the course taught. For example, National Instrument (NI) have lab View, My Rio and compact Rio for the students to learn the concept more clearly by introducing these components along with the conventional method of teaching. Similarly, OPALRT platforms recently an equipment which is used for validation and testing of the power electronics in any real-time application. Students can be exposed to this modern equipment to under the concept in easier way with depth of knowledge.

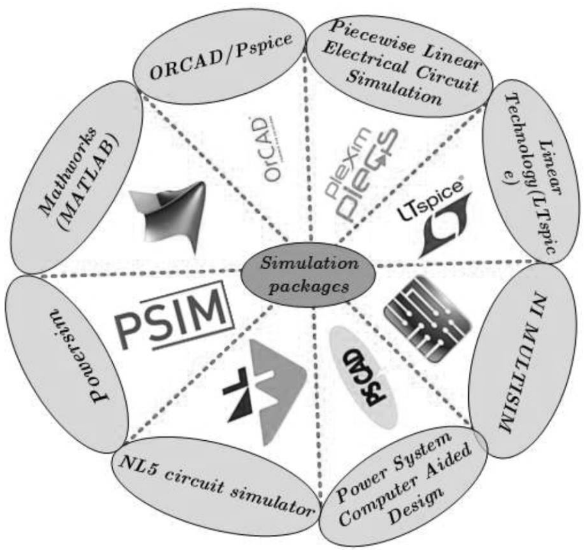


Fig. 4: Simulation packages for power electronic circuits

In addition to this, several controllers loke dSPACE, FPGA, DSP are available for designing the controllers for power converters designed and validated. Now a days, all the renewable power source emulators are available along with the power conditioning unit to learn and analyse about the integration of the power converters with grid for distributed generation.

3. Mathematical Model Of A Quadratic Boost Converter With Dcl Cell (qbdcl)

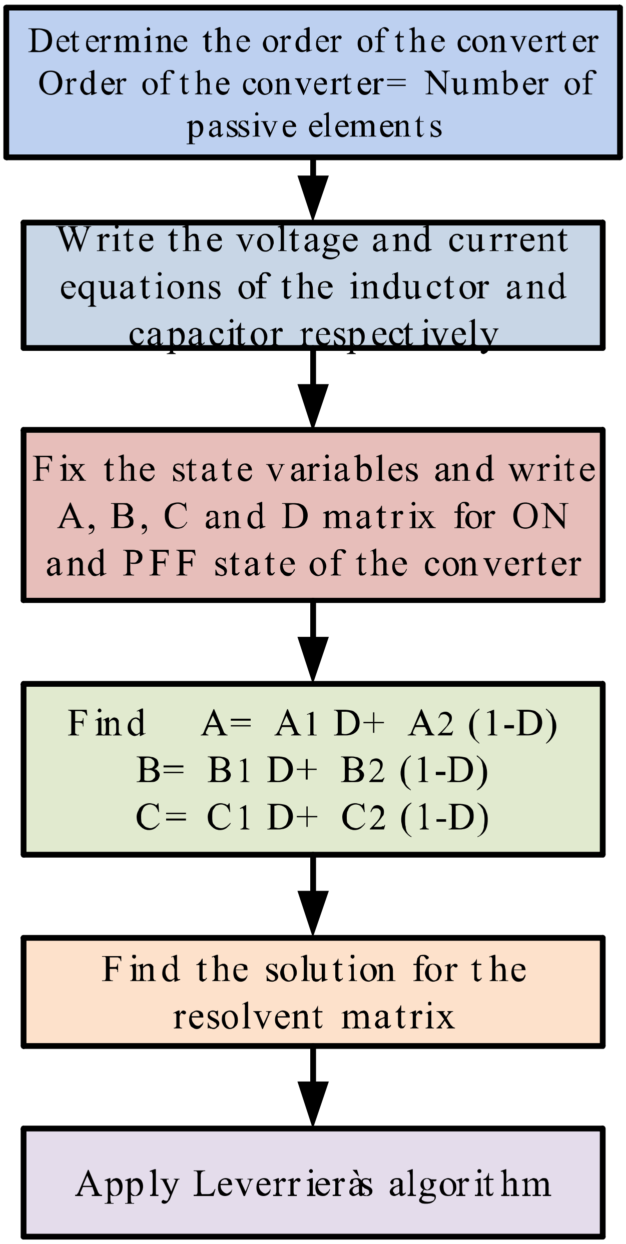


Fig. 5: Mathematical modelling of QBDCL converter using SSA

One of the most popular modelling technique 'SSA' is generally used to obtain a higher-order DC-DC converter transfer function. This is a simple modelling technique purely based on matrix algebra. Resolvent matrix (sI-A)-1 calculation becomes troublesome as the matrix's order increases, making it more prone to error and difficult to arrive at the transfer function. This method uses the scalar Laplace operator 's', making it challenging to calculate through digital computers.

One such algorithm named Leverriers Algorithm [10] comes very handily to calculate the matrix's inverse. This is a well-known algorithm, and it has been reported in very few articles for computing the inverse of the resolvent matrix (sI-A)-1 of the dc-dc converter during its transfer function determination.

$$X(t) = Ax(t) + Bu(t) \quad (1)$$

$$Y(t) = Cx(t) + Du(t) \quad (2)$$

The state-space equation for QBDCL converter for ON and OFF modes is presented as

$$\dot{X_1}(t) = A_1x(t) + B_1u(t) \quad (3)$$

$$\dot{X_2}(t) = A_2x(t) + B_2u(t) \quad (4)$$

The output equations at ON and OFF modes are

$$y(t) = C_1x(t) + D_1u(t) ;$$

$$y(t) = C_2x(t) + D_2u(t) \quad (5)$$

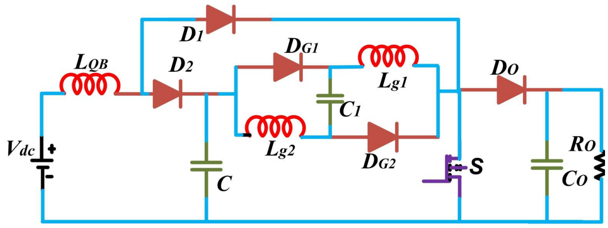


Fig. 6: Quadratic boost with DCL cell (QBDCL) converter

The steps involved in modelling the dc-dc converter is presented in fig 5.

The generalized state-space model of a system is given by

To illustrate the methodology, quadratic boost converter with the diode-capacitor-inductor (DCL) cell which is depicted in Fig 6 is chosen. Since the number of passive components is high, this converter is considered for further analysis. The state, input, and output matrix of shoot and non-shoot through the converter period are obtained and tabulated in table 1.

Table 1 : State-space Representation of Qbdcl Converter

State-space representation of QBDCL converter		
ON state		
State matrix	Input matrix	Output and feedforward matrix
$A_1 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & {}^{1}/_{L_{g1}} & 0 \\ 0 & -{}^{3}/_{C} & 0 & 0 \\ 0 & 0 & 0 & -{}^{1}/_{R_O C_O} \end{pmatrix}$	$B_1 = \begin{pmatrix} {}^{1}/_{L_{QB}} \\ 0 \\ 0 \\ 0 \end{pmatrix}$	$C_1 = (0 \quad 0 \quad 0 \quad 1)$ $D_1 = (0)$
OFF state		
$A_2 = \begin{pmatrix} 0 & 0 & -{}^{1}/_{L_{QB}} & 0 \\ 0 & 0 & {}^{1}/_{3L_{g1}} & -{}^{1}/_{3L_{g1}} \\ {}^{1}/_{C} & -{}^{1}/_{C} & 0 & 0 \\ 0 & {}^{1}/_{C_O} & 0 & -{}^{1}/_{R_O C_O} \end{pmatrix}$	$B_2 = \begin{pmatrix} {}^{1}/_{L_{QB}} \\ 0 \\ 0 \\ 0 \end{pmatrix}$	$C_2 = (0 \quad 0 \quad 0 \quad 1)$ $D_2 = (0)$
Combining ON and OFF state		
$A = \begin{pmatrix} 0 & 0 & -{}^{D'}/_{L_{QB}} & 0 \\ 0 & 0 & {}^{[1+2D]}/_{3L_{g1}} & -{}^{D'}/_{3L_{g1}} \\ {}^{D'}/_{C} & -{}^{[1+2D]}/_{C} & 0 & 0 \\ 0 & {}^{D'}/_{C_O} & 0 & -{}^{1}/_{R_O C_O} \end{pmatrix}$	$B = \begin{pmatrix} {}^{1}/_{L_{QB}} \\ 0 \\ 0 \\ 0 \end{pmatrix}$	$C = (0 \quad 0 \quad 0 \quad 1)$ $D = (0)$

In A, B, C and D matrix, substitu D+$\tilde{d}$ in the place of d and derive the state-space equation with perturbation.

$$\begin{pmatrix} \widetilde{i_{LQB}} \\ \widetilde{i_{L21}} \\ \widetilde{v_C} \\ \widetilde{v_{CO}} \end{pmatrix} = \begin{pmatrix} 0 & 0 & -{}^{D'}/_{L_{QB}} & 0 \\ 0 & 0 & {}^{[1+2D]}/_{3L_{g1}} & -{}^{D'}/_{3L_{g1}} \\ {}^{D'}/_{C} & -{}^{[1+2D]}/_{C} & 0 & 0 \\ 0 & {}^{D'}/_{C_O} & 0 & -{}^{1}/_{R_O C_O} \end{pmatrix} \begin{pmatrix} \widetilde{i_{LQB}} \\ \widetilde{i_{Lg1}} \\ \widetilde{v_C} \\ \widetilde{v_{CO}} \end{pmatrix} + \begin{pmatrix} {}^{V_C}/_{L_{QB}} & {}^{1}/_{L_{QB}} \\ {}^{(2V_C + V_{CO})}/_{3L_{g1}} & 0 \\ -{}^{(I_{LQB} + 2I_{Lg1})}/_{C} & 0 \\ -{}^{I_{Lg1}}/_{C_O} & 0 \end{pmatrix} \begin{pmatrix} \tilde{d} \\ \widetilde{v_g} \end{pmatrix}$$

4. Flowchart For Leverrier's Algorithm For Dc-dc Converter

Let the matrix A be of order n x n, then according to Leverrier's algorithm resolvent matrix is given by

$$(sI - A)^{-1} = \frac{Adj(sI - A)}{[sI - A]} = \frac{P_{n-1}s^{n-1} + P_{n-2}s^{n-2} + \cdots \quad P_1 s + P_O}{s^n + b_{n-1}s^{n-1} + b_{n-2}s^{n-2} + \cdots \quad b_1 s + b_O} \tag{7}$$

Here, Pi is a nxn matrices and bi are scalar

Step 1 : Define P_{n-1} as n^{th} order identity matrix and find coefficient b_{n-1}

Substitute the values of 'b' and 'p' to get final value of resolvent matrix.

$$P_{n-1} = I_n \tag{8}$$

Where I_n is the nth order identity matrix

$$b_{n-1} = -trace(P_{n-1}A) \tag{9}$$

Step 2 : Calculate next P_{n-2} and coefficient b_{n-2}

$$P_{n-2} = P_{n-1}A + b_{n-1}I_n \tag{10}$$

$$b_{n-2} = -\frac{1}{2} trace(P_{n-2}A) \tag{11}$$

For jth sequence calculate as P_j and b_j as

$$P_{n-j} = P_{n-j+1}A + b_{n-j+1}I_n \tag{12}$$

$$b_{n-j} = -\frac{1}{j} trace(P_{n-j}A) \tag{13}$$

Step n : Finally calculate P_o and b_o

$$P_O = P_1 A + b_1 I_n \tag{14}$$

$$b_O = -\frac{1}{n} trace(P_O A) \tag{15}$$

Input to output transfer function is derived by taking Laplace transform of the output equation which is obtained as

y (s) = C [sI-A] ^ (-1) Bu (s) (16)

In equation (16), A, B and C matrix are substituted from the Table I and simplified by the Leverrier's algorithm. The MATLAB coding to obtain the numerator and denominator of the transfer function is given as

```
syms LQB Lg1 D D' C Ro Co S
A= [0 0 -D')/LQB 0;0 0 (1+2D)/(3*Lg1) -D'/(3*Lg1); D'/C -(1+2D)/C 0 0;0 D'/Co 0 (-1/(Ro*Co))];
B= [1/LQB 0 0];
C= [0 0 0 1];
P3=eye (4);
b3=-trace(P3*A);
Q2=(P3*A) +(b3*P3);
b2=-0.5*trace(P2*A);
Q1=(P2*A)+(b2*P3);
b1=-(1/3) *trace(Q1*A);
Po=(P1*A) +(b1*P3);
bo=-(1/4) *trace (Po*A);
Denominator=S^4+(b3*S^3) +(b2*S^2) +(b1*S) +bo
Numerator=B*[(P3*S^3) +(P2*S^2) +(P1*S) +Po] *C
```

Using the above coding, the numerator and denominator of the input to output transfer function is determined as

$$\frac{\widetilde{v_O(s)}}{\widetilde{v_g}(s)} = \frac{\frac{1+2D}{D'^2}}{\left[1+s\left\{\frac{[1+2D]^2L_1}{D'^4R_O}+\frac{3L_{g1}}{D'^2R_O}\right\}+s^2\left\{\frac{[1+2D]^2L_{QB}C_O}{D'^4}+\frac{L_{QB}C_1}{D'^2}+\frac{3L_{g1}C_O}{D'^2}\right\}+s^3\left\{\frac{3L_{QB}L_{g1}C}{D'^4R_O}\right\}+s^4\left\{\frac{3L_{QB}L_{g1}CC_O}{D'^4}\right\}\right]} \quad (17)$$

Further analysis is carried out for the following :

Power= 40 W, Input voltage (Vg)= 12 V, output voltage (Vo)= 96 V, Inductor LQB= 15 µH, Lg1 =120 µH, switching frequency (fSW) = 60 kHz, Duty cycle (D) = 0.5 and load resistance (Ro) = 230 Ω. By subtituting these values in equation (17), the input to output transfer function is obtained as

$$\frac{\widetilde{v_O(s)}}{\widetilde{v_g}(s)} = \frac{18.518X10^{17}}{S^4+0.484X10^4S^3+1.239X10^9S^2+0.341X10^{13}S+2.314X10^{17}} \quad (18)$$

Fig 7 represents the step response obtained from the input to output transfer function of full order converter from Matlab.

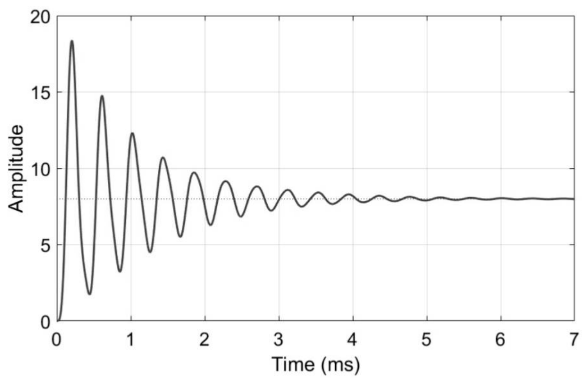


Fig .7: Step response full order QBDCL converter

I. Flowchart For Pole Clustering Technique For Dc-dc Converter

Mathematical models are carried out to achieve desired performance from a dynamic system. Systems that yields composite models are tough to analyze due to computational cost, or storage constraints. This problem can be solved using model reduction techniques that tends to store the dominant characteristics of the model. This model reduction produces analyzable models whose features like transient response, static response, stability is preserved. This paper follows the improved pole clustering method for reducing the order of the model. Fig 8 depicts the steps involved in applying the pole clustering technique to the dc-dc converter. The model reduction steps involve first calculation of the denominator then numerator.

Let, consider a higher-order system as

$$G_{vFO}(s) = \frac{Num(s)}{Den(s)} = \frac{c_O+c_1s+\cdots+c_{n-1}s^{n-1}}{f_O+f_1s+f_2s^2+\cdots+f_ns^n} \quad (18)$$

Similarly, the reduced-order model be of the form

$$G_{vRO}(s) = \frac{Num(s)}{Den(s)} = \frac{u_O+u_1s+\cdots+u_{n-1}s^{n-1}}{v_O+v_1s+v_2s^2+\cdots+v_ns^n} \quad (19)$$

5.1 Calculation of denominator:

The rules for Clustering of poles:

- Distinct clusters are segregated for real and complex poles.
- Poles lying in the left and right half of s plane are separately grouped.
- Purely imaginary and zero poles are retained in the approximate system.

Suppose poles are given by the following equation

$$Den(s) = (s+\alpha_1)(s+\alpha_2)(s+\alpha_3)..(s+\alpha_r)(s+\alpha_{r+1})\dots(s+\alpha_{2r})(s+\alpha_{2r+1})\dots(s+\alpha_n) \quad (20)$$

Assume that the model is needed to follow up 'rth' reduce order, then the number of clusters formed is equal to r. The first pole is placed in first cluster, second in the next cluster, similarly rth pole in rth cluster, again (r+1)th pole in the first cluster, (r+2) in second, (2r) in rth cluster and the process continues until all the poles are set up in clusters. Each pole in a cluster is arranged in ascending order considering only magnitude value.

Setup the model taking the cases given below

Case 1: - All poles are real

The denominator is obtained as

$$Den(s) = (s-\partial_1)(s-\partial_2)(s-\partial_3)\dots..(s-\partial_r) \quad (21)$$

Case 2: -All poles are complex

Apply the algorithm for the real and imaginary parts separately. The denominator of the lower-order system is given as

$$Den(s) = (s-\alpha_1 \pm j\beta_1)(s-\alpha_2 \pm \beta_2)\dots. \quad (22)$$

Case 3: Real and Complex pole

An improved clustering algorithm is applied independently for both real and complex terms. For rth order reduced-order system, let γ be the cluster center for real poles, and μ be the cluster center for complex poles. Then denominator is given by

$$Den(s) = \prod_{i=1,j=1}^{\gamma,\frac{\mu}{2}} (s-\partial_i)(s-\alpha_j \pm \beta_j)\dots \quad (23)$$

5.2 Calculation of numerator:

The numerator of the reduced-order model is calculated using simple mathematical computation [12-14]. It is attained by equating the transfer function of the original order and reduced order converter as stated below

$$\frac{g_o + g_1 s + g_2 s^2 + \cdots g_{n-1}s^{n-1} + g_n s^n}{j_o + j_1 s + j_2 s^2 + \cdots j_{m-1}s^{m-1} + j_m s^m} = \frac{q_o + q_1 s + q_2 s^2 + \cdots q_{r-1}s^{r-1} + q_r s^r}{r_o + r_1 s + r_2 s^2 + \cdots r_{q-1}s^{q-1} + r_q s^q} \quad (24)$$

'r' number of equations are obtained by equating the powers of S.

$$\left.\begin{array}{l} g_o r_o = j_o q_o \\ g_o r_1 + g_1 r_o = j_o q_1 + j q_o \\ g_o r_2 + g_1 r_1 + g_2 r_0 = j_o q_2 + j q_1 + j q_0 \\ \vdots \end{array}\right\} \quad (25)$$

By rearranging the equations (25), the numerator of the transfer function is obtained. The numerator polynomial coefficients can easily be determined from the known coefficients of the denominator polynomial.

Consider the fourth-order transfer function of the QBDCL converter in equation (18) to reduce to second-order transfer function using the technique

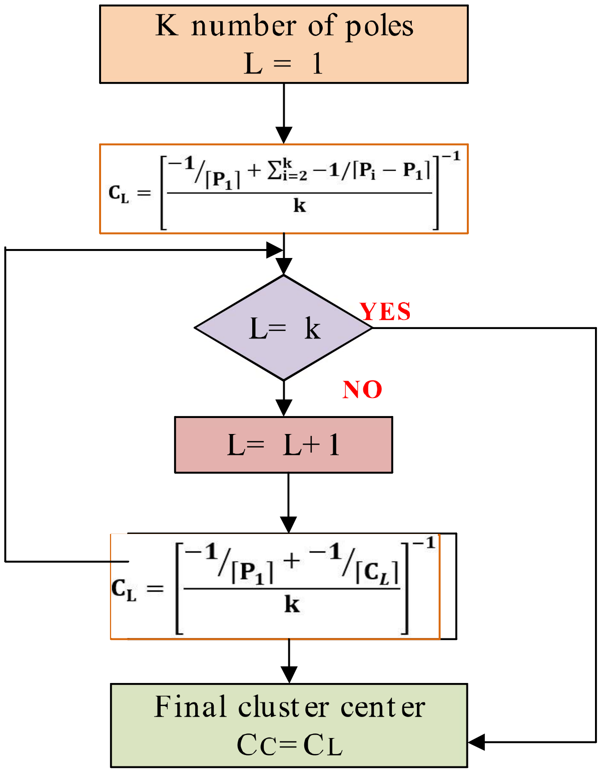


Fig 8: Steps to proceed with pole clustering technique for DC-DC converter

mentioned above. The poles of the full order and reduced order are presented in Table II.

Table 2 : Poles of the full order and reduced-order qbdcl converter

Poles of the full order QBDCL converter
$\alpha_1 = -1585 + j31647;\ \alpha_2 = -1585 - j31647$
$\alpha_3 = -839 + j15161;\ \alpha_4 = -839 - j15161$
Poles of the reduced-order QBDCL converter
$\alpha_1 = -813.6 + j15471;\ \alpha_2 = -813.6 - j15471$

The numerator of the transfer function is calculated by equation (18) with the equation obtained from the poles of the reduced order as per the equation (24). By equating the power of the S, it is acquired as

$$\frac{18.518X10^{17}}{2.314X10^{17}} = \frac{q_O}{240.03X10^6} \quad (26)$$

Solving the equation (26), we obtain the numerator of the reduced-order converter is

Num = 1920.92X106 (27)

After completing the calculation of numerator and denominator, the derived reduced-order transfer function is

$$\frac{\widetilde{v_O}(s)}{\widetilde{v_g}(s)} = \frac{1920.92X\ \ ^6}{S^2+16\ \ .2S+240.03X10^6} \quad (28)$$

Fig 9 represents the step response obtained from the input to output transfer function of reduced-order converter from Matlab.

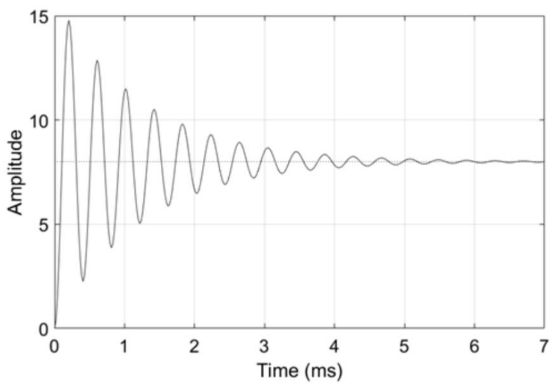


Fig. 9: Step response reduced order QBDCL converter

6. Flowchart For Controller Design Of Dc-dc Converter

Due to the simplicity in design, the PID controller is the most commonly used control strategy in industries, and its general block diagram is depicted in Fig 10. The Proportional and integral parameters create a more significant impact on the system's performance, and henceforth, optimal values are essential. The utmost common method of PI tuning is the Ziegler-Nichols tuning method. The simplicity of this method is that its inherent principle in determining the value of Kp and KI. With the system's step response, the Kp value is set to a small value by keeping the KI to zero. The response of the system is observed until it reaches neutral stability [22]. After that, using the formulae given in Table 2, the controller parameter values are obtained. Though, this alike response cannot be obtained for all the systems by fine-tuning the Kp values.

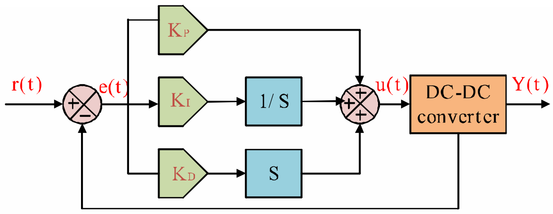


Fig. 10: General block diagram for DC-DC converter with PID

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^k e(\tau)d\tau + T_d\frac{de(t)}{dt}\right)$$
(29)

Simplifying the expression (29), results to

$$u(t) = K_p e(t) + K_I\int_0^k e(\tau)d\tau + K_D\frac{de(t)}{dt}$$
(30)

Where $K_I = \frac{K_P}{T_i};\ K_D = K_P T_d$

Thus, the final expression of the PID controller is written as

$$G_{PID}(s) = K_P + \frac{K_I}{S} + K_D S \quad (31)$$

Fig 11 illustrates the steps involved in the determination of PID parameters with Ziegler-Nichol's tuning. Table III presents the formula used to calculate the PID parameters with the second method of step response-based Ziegler-Nichol's tuning.

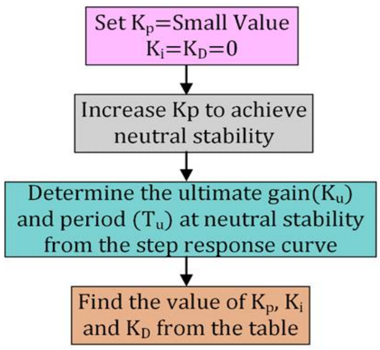


Fig 11: Steps to proceed with Ziegler-Nichols tuning for DC-DC converter

Table 3 : Formula To Tune Controller Parameters in the Pid Controller with Ziegler-nichols Tuning

Controller	Kp	Ti	Td
PID	0.6Ku	Tu/2	Tu/8
P	05Ku	-	-
PI	0.45Ku	Tu/1.2	-
PD	0.8Ku	-	Tu/8
No overshoot	0.2Ku	Tu/2	Tu/3

According to Fig 11, the Kp value is set to a smaller value, and the step input response is observed. If the oscillation reaches neutral stability, then the Kp value is set as Ku, and the time period is noted in the sustained oscillation to set as Tu. Finally, the KI is calculated by determining the value of Ti.

Table 4 : Values Determined By Ziegler-nichols Tuning (step Response)

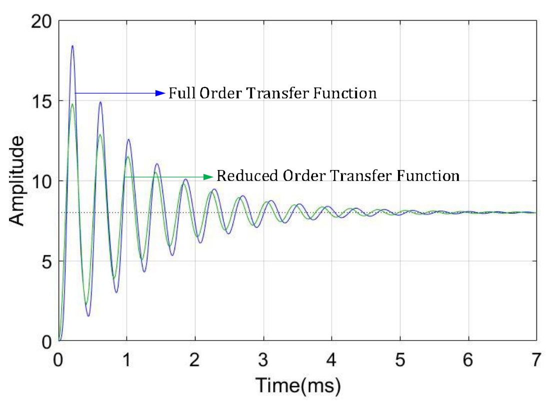
Ku	Tu	Ti	Kp	K_I
0.011	0.001	8.33e-4	0.005	6

Using the Table IV, the transfer function of PI controller is determined by substituting the values to (31).

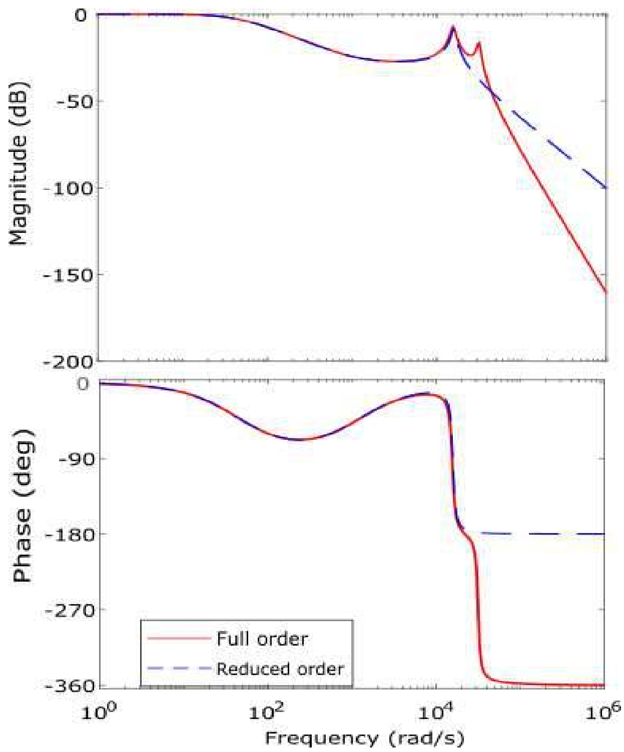
$$G_{PI}(s) = \frac{0.005S + 6}{S} \quad (32)$$

7. Validation of the Algorithms

The open-loop response of equations (18) and (28) is determined and presented in Fig 12 (a). From this figure, it is observed that the response obtained from the full order transfer function matches closely with the reduced-order transfer function. To validate the results further, the two transfer functions' bode plot are compared and presented in Fig 12 (b). The bode plot matches closely with a slight deviation.



(a)



(b)

Fig. 12: Comparison of results (a) Step response of full-order and reduced-order QBDCL converter (b) Bode plot of full-order and reduced-order QBDCL converter

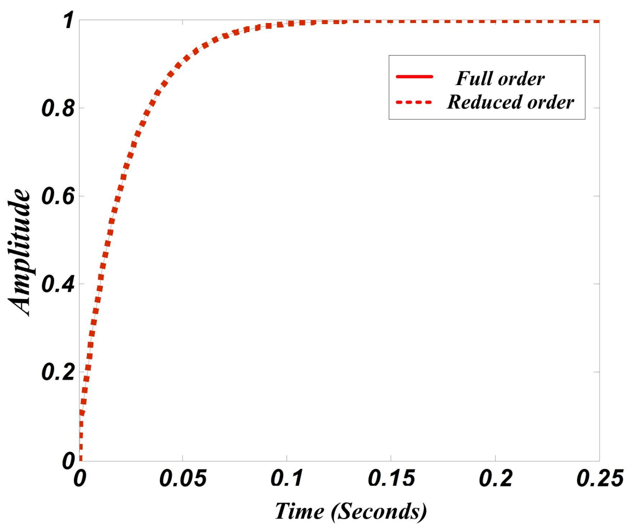


Fig. 13: Comparison of closed-loop response obtained for full-order and reduced-order QBDCL converter

Table 5 :
Comparison Of Time-domain Specification

Input to output transfer function	Poles	Zeroes	Time-domain specification
Full order open loop transfer function	−1585 + ▯31647 −1585 − 31647 −839 + ▯15161 −839 − ▯15161	Nil	Overshoot= 130% Rise time= 0.05 msec Settling time= 0.0042 sec
Reduced-order-Open-loop transfer function	−813.6 + ▯15471 −813.6 − ▯15471	Nil	Overshoot= 90% Rise time= 0.07 msec Settling time= 0.004 sec
Closed-loop transfer function with full-order PI controller	1.0e+04* 0.0000 + 0.0000i 1.0e+04* -0.1261 - 3.1677i 1.0e+04* -0.1261 + 3.1677i 1.0e+04* -0.0913 + 1.5149i 1.0e+04* -0.0913 - 1.5149i	-1200	Overshoot= 0%
Closed-loop transfer function with reduced-order PI controller	1.0e+04* 0.0000 + 0.0000i 1.0e+04* -0.0814 + 1.5472i 1.0e+04* -0.0814 - 1.5472i	-1200	

Finally, (32) is integrated with equations (18) and (28) to receive the closed-loop response of the system. The response received from the closed-loop system of the full order and reduced order is presented in Fig 13. The time-domain parameters obtained from the open-loop and closed-loop response of full-order and reduced-order transfer functions are tabulated in table 5 for comparison. It is noted that the pole clustering technique is best suited to the dynamic analysis of the dc-dc converter, especially for the higher-order transfer function.

This paper has detailed the study carried out in the dynamic analysis of the converter. It introduces the steps involved in analyzing the mathematical model of the converter to design the closed-loop controller. According to Bloom's taxonomy, this methodology can be incorporated in post-graduate curriculum of power electronics courses for improving their design skill. We described the procedure for finding a solution to the resolvent matrix with Leverrier's algorithm. The Matlab coding for the matrix solution is given, which can be used as a teaching tool for finding the transfer function of a newly derived dc-dc converter. Furthermore, the flowchart of the various techniques incorporated is given, which can be used as teaching to explain the converter's mathematical modelling.

An illustrative example is given to explain the proposed methodology. Quadratic boost converter with DCL cell is chosen for explaining the procedure involved in Leverrier's algorithm, pole clustering technique, and PI Ziegler-Nicholas tuning.

Pole clustering technique is used to reduce the order of the transfer function. The full-order converter's open-loop response is compared with the reduced-order converter to validate the result obtained from the pole clustering technique. It is noted that both the response closely matches the similar value of time-domain parameters. The open-loop response is used to find the PI controller's Kp and Ki value with Ziegler-Nicholas step response second method of tuning. The determination of these values is made more accessible to the response obtained from Matlab. Finally, the closed-loop response is determined by combining the PI controller transfer function with the dc-dc converter's transfer function.

References

[1] Z. Ullah, A. Lajis, M. Jamjoom, A. H. Altalhi, J. Shah and F. Saleem (2019) "A Rule-Based Method for Cognitive Competency Assessment in Computer Programming Using Bloom's Taxonomy," in IEEE Access, 7,64663-64675.

[2] A.A. Ursani , A. A. Memon, B. S. Chowdhry (2014),"Bloom's Taxonomy as a Pedagogical Model for Signals and Systems", International Journal of Electrical Engineering Education, 51(2)162-173.

[3] P. Azer and A. Emadi,(2020) "Generalized State Space Average Model for Multi-Phase Interleaved Buck, Boost and Buck-Boost DC-DC Converters: Transient, Steady-State and Switching Dynamics," in IEEE Access, vol. 8, pp. 77735-77745, doi: 10.1109/ACCESS.2020.2987277.

[4] A. Ayachit and M. K. Kazimierczuk,(2019) "Averaged Small-Signal Model of PWM DC-DC Converters in CCM Including Switching Power Loss," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 66, no. 2, pp. 262-266, doi: 10.1109/TCSII.2018.2848623.

[5] P., S., Divya, N., Sathik, J., A., L., K., V. and Almakhles, D. (2021), "A comprehensive study on various dc–dc converter voltage-boosting topologies and their applications", Circuit World, Vol. ahead-of-print No. ahead-of-print.

https://doi.org/10.1108/CW-12-2020-0338.

[6] J. Divya Navamani, A. Lavanya, Dhafer Almakhles, M. Jagabar Sathik, (2022), A review on segregation of various high gain converter configurations for distributed energy sources, Alexandria Engineering Journal, Volume 61, Issue 1,Pages 675-700,ISSN 1110-0168,https://doi.org/10.1016/j.aej.2021.06.026.

[7] Divya Navamani, K. Vijayakumar, R. Jegatheesan, A. JasonMano Raj,(2018), " Reliability analysis and SFG modeling of a newmodified Quadratic boost DC-DC converter", Journal ofMicroelectronics, Electron. Compon. Mater. 48(1), 3–18.

[8] Divya Navamani Jayachandran, Vijayakumar Krishnasamy,Jegatheesan Ramiah, (2018), "Stability Analysis of a Novel Switched Inductor Based Quadratic Boost DC-DC Converter+, Adv.Electric. Electron. Eng. 15(5) (2018) 1–11.

[9] J. Chen and K. D. T. Ngo,(2001) "Alternate forms of the PWM switch model in discontinuous conduction mode [DC-DC converters]," in IEEE Transactions on Aerospace and Electronic Systems, vol. 37, no. 2, pp. 754-758, doi: 10.1109/7.937489.

[10] D. Czarkowski and M. K. Kazimierczuk, (1993), "Energy-conservation approach to modeling PWM DC-DC converters," in IEEE Transactions on Aerospace and Electronic Systems, vol. 29, no. 3, pp. 1059-1063,doi: 10.1109/7.220955.

[11] Ramesh Komarasamy, Nirmalkumar Albhonso and Gurusamy Gurusam (2011)," Order reduction of linear systems with an improved pole clustering", Journal of Vibration and Control, Journal of Vibration and Control,18(12),1876–1885.

[12] J.Singh, C.B.Vishwakarma, K.Chattterjee (2016), "Biased reduction method by combining improved modified pole clustering and improved Padé approximations". Applied Mathematical Modelling,40(2),1418-1426.

[13] Kaushal Ramawat, Manisha Bhandari, Anuj Kumar,"Model Order Reduction by Pade Approximation and Improved Pole Clustering Technique" Energy Technology & Ecological Concerns: A Contemporary Approach.

[14] A. Sikander, R. Prasad (2017),"A new technique for reduced-order modelling of linear time-invariant system", IETE J. Res. 63(3),316–324.

[15] Arvind Kumar Prajapati, Rajendra Prasad (2020)" A New Model Reduction Method for the Linear Dynamic Systems and Its Application for the Design of Compensator", Circuits, Systems, and Signal Processing, 39,2328–2348.

[16] W. L. Torres, I. B. Q. Araujo, J. B. Menezes Filho and A. G. Costa Junior(2017), "Mathematical Modeling and PID Controller Parameter Tuning in a Didactic Thermal Plant," in IEEE Latin America Transactions,15(7),1250-1256,

[17] A. S. Bazanella, L. F. A. Pereira and A. Parraga (2017), "A New Method for PID Tuning Including Plants Without Ultimate Frequency," in IEEE Transactions on Control Systems Technology, vol. 25 (2),637-644.

[18] A. Mughees and S. A. Mohsin(2020), "Design and Control of Magnetic Levitation System by Optimizing Fractional Order PID Controller Using Ant Colony Optimization Algorithm," in IEEE Access, 8,116704-116723.

[19] A. H. Khan, Z. Shao, S. Li, Q. Wang and N. Guan(2020), "Which is the best PID variant for pneumatic soft robots? an experimental study," in IEEE/CAA Journal of Automatica Sinica,7(2),451-460.

[20] M. S. Ashik, V. Vijayan Nair, P. K. Boppudi and M. Sanjay(2019), "Particle Swarm Optimization of Proportional-Integral Controller Parameters for Phase Shifted Full Bridge DC-DC Converter for Hybrid and Electric Vehicles," International Conference on Intelligent Computing and Control Systems (ICCS), Madurai, India,836-840.

[21] Fazilah Hassan, Argyrios C. Zolotas and Tim Smith(2017)," Optimized Ziegler-Nichols based PID Control Design for Tilt Suspension", Journal of Engineering Science and Technology Review 10 (5), 17 – 24.

[22] Oladimeji Ibrahim, Nor Zaihar Yahaya, Nordin Saad(2016)," Comparative Studies of PID Controller Tuning Methods on a DC-DC Boost Converter", 2016 6th International Conference on Intelligent and Advanced Systems (ICIAS).