Journal of Interdisciplinary Mathematics
ISSN: 0972-0502 (Print), ISSN: 2169-012X (Online)
Vol. 29 (2026), No. 3, pp. 607–616
DOI : 10.47974/JIM-2495

Enhancing electronics design with complex variable theory in industrial applications

Nilesh M. Pawar †
Department of Information Technology
Yadavrao Tasgaonkar Institute of Engineering and Technology
Raigad 410201
Maharashtra
India

Raju M. Sairise *
Department of Electronics & Telecommunication Engineering
Yadavrao Tasgaonkar College of Engineering and Management
Raigad 410201
Maharashtra
India

Kumari Shipra §
School of Engineering & Technology
Noida International University
Greater Noida 203201
Uttar Pradesh
India

Malem Mangal Laishram ‡
Symbiosis Centre for Advanced Legal Studies and Research (SCALSAR)
Symbiosis Law School Pune (SLS-P)
Symbiosis International (Deemed University)
Pune 411014
Maharashtra
India

† *E-mail:* nmp206@gmail.com
* *E-mail:* rairise566@gmail.com (Corresponding Author)
§ *E-mail:* kumari.shipra@niu.edu.in
‡ *E-mail:* laishram.mangal@symlaw.ac.in

Egambergan Khudaynazarov [@]
Department of General Professional Sciences
Mamun University
Khiva 220900
Uzbekistan

Aparna Shrinivas Shirkande [#]
Department of Electronics and Telecommunication
S B Patil College of Engineering
Indapur
Pune 413106
Maharashtra
India

Abstract

This essay will examine the use of complex variable theory to make the industrial electronics design more appropriate. Complex analysis is a field of mathematics that assists engineers to know more and better about solving complex problems involving electric fields, signal processing and circuit stability. The complicated factors used allow it to be easier to control and analyze AC circuits and control systems resulting in more accurate designs and more efficient operations. Simpler calculations and superiority in estimating the behavior of electronic components in various scenarios are suitable in industrial applications. The paper demonstrates how the techniques of complex variables can be applied in practice to enhance the stability of the system and the ways of the circuits optimization. The findings indicate that inclusion of the complicated variable theory in the electronics designing process is a big difference in the advancement and achievement of industrial electronics.

Subject Classification: *30-03, 30A05.*

Keywords: *Complex variable theory, Electronics design, Industrial applications, Signal processing, Circuit stability.*

1. Introduction

With the fast advancement of industrial electronics, it requires more complex design approaches which can address the manner in which circuits and systems respond in complex manners. Electronic design in industry is commonly concerned with control systems, interaction of electromagnetic fields, alternating current (AC) circuits and signal modulation. All these things may behave in nonlinear ways as well as complex ways [1]. Many tasks can be tackled well with traditional real-variable approaches, but they do not always

[@] *ORCID-ID:* `0009-0000-1210-8113`

[@] *E-mail:* `e.xudaynazarov@mamunedu.uz`
[#] *E-mail:* `kaleaparna5@gmail.com`

provide models and solutions of these complex problems, and may result in less than optimal solutions and wasted time and money. Complex number theory The complex number theory of functions provides us with a powerful and beautiful means of handling such problems [2],[3]. Efforts to take the study to complex plane would enable engineers to gain knowledge on how circuits work, what makes them stable, and how they respond to frequency changes. Complex analysis has tools such as analytic functions, contour integration, and residue calculus that simplify the task of evaluating frequently used integrals and differential equations [4]. Speaking about greater detail, it is more convenient to demonstrate periodic signals and phasors with the help of complex variables. This transforms the form of differential equations into simpler algebraic forms [5].

2. Methodology

2.1. *Integration of complex variable techniques into design processes*

Complex variable techniques when complex variable techniques are added to the process of designing electronics, a mathematical technique of complex analysis has to be integrated into the normal engineering work processes.

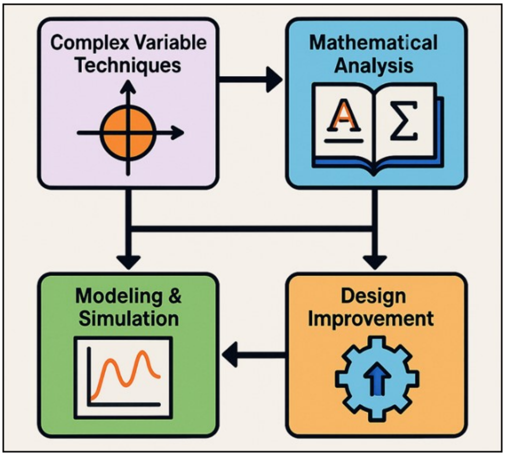

Figure 1

Integration Framework of Complex Variable Techniques in Electronics Design Processes

Figure 1 gives an example of integration of complex variables in the designing of electronics [6], [7]. The techniques assist in making circuit equations easier to comprehend and examine by design engineers leading to more effective optimization procedures.

Definition (Complex Function): A function f: $\mathbb{C} \to \mathbb{C}$ is said to be complex differentiable at $z_0 \in \mathbb{C}$ if the limit

$$\frac{f'(z^0)=\lim_{z\to z^0}[f(z)-f(z^0)]}{(z-z^0)} \tag{1}$$

exists.

Equation (Phasor Representation): *Any sinusoidal signal* $\boldsymbol{v(t) = V\_m\,cos(\omega t + \varphi)}$ *can be represented as a complex phasor:*

$$\tilde{V} = \boldsymbol{V_m e^{j\varphi}} \tag{2}$$

Theorem (Cauchy-Riemann Equations): *For* $\boldsymbol{f(z) = u(x,y) + iv(x,y)}$ *to be analytic, the partial derivatives must satisfy:*

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y}, \quad \frac{\partial u}{\partial y} = -\frac{\partial v}{\partial x} \tag{3}$$

Proof Sketch: Using the limit definition of complex differentiability, equate the limit from different directions and obtain the Cauchy-Riemann equations.

Additional Equations:

Complex Conjugate:

$$\dot{z} = \boldsymbol{x - jy,\ for\ z = x + jy} \tag{4}$$

Modulus of Complex Number:

$$|\boldsymbol{z}| = \boldsymbol{sqrt(x^2 + y^2)}$$

$$\boldsymbol{e^{\{j\theta\}} = cos\theta + j\,sin\theta} \tag{5}$$

Analytic Function Integral (Cauchy Integral Formula):

$$\boldsymbol{f(z^0) = \left(\frac{1}{2\pi i}\right)\oint_C \left[\frac{f(z)}{(z-z^0)}\right] dz} \tag{6}$$

Laurent Series Expansion:

$$\boldsymbol{f(z) = \Sigma_{\{n=-\infty\}}^{\infty} a_n (z - z^0)^n} \tag{7}$$

2.2. *Analytical modeling of electronic components using complex variables*

When you use complicated factors in analytical modelling of electronic components, you can get very accurate mathematical accounts of how they change over time [8]. Engineers can clearly show sinusoidal steady-state reactions and frequency-dependent features by writing voltage, current, and resistance as complex numbers [9]. By turning differential equations about how components work, like in capacitors, inductors, and transistors, into algebraic forms, complex variable models make them easier to solve.

Equation (Impedance of RLC Circuit): *The total impedance Z in complex form for series RLC circuit:*

$$\boldsymbol{Z = R + j\left(\omega L - \frac{1}{\omega C}\right)} \tag{8}$$

Definition (Complex Impedance): *Impedance Z is a complex quantity* $\boldsymbol{Z = R + jX}$*, where R is resistance and X is reactance. [10]*

Equation (Transfer Function): For a linear time-invariant (LTI) system, the transfer function in complex frequency domain is:

$$\boldsymbol{H(s) = \frac{V_{out(s)}}{V_{in(s)}}} \tag{9}$$

where $\boldsymbol{s = \sigma + j\omega}$ is the complex frequency variable.

Additional Equations:

Admittance Y of RLC Circuit:

$$\boldsymbol{Y = \frac{1}{Z} = G + jB = \frac{1}{R} + j\left(\omega C - \frac{1}{\omega L}\right)} \tag{10}$$

Phasor Voltage and Current Relationship:

$$\tilde{V} = \boldsymbol{Z}\,\hat{I}$$

Resonant Frequency in RLC Circuit:

$$\boldsymbol{\omega^0 = \frac{1}{sqrt(LC)}} \tag{11}$$

Quality Factor Q:

$$\boldsymbol{Q = \frac{(\omega^0 L)}{R} = \frac{1}{(\omega^0 R\, C)}} \tag{12}$$

Impedance of Transmission Line:

$$\boldsymbol{Z^0 = sqrt\left(\frac{(R + j\omega L)}{(G + j\omega C)}\right)} \tag{13}$$

Complex Power S:

$$\boldsymbol{S = P + jQ = V\, I* = V\_rms\, I\_rms\, cos\phi + j\, V\_rms\, I\_rms\, sin\phi}$$

2.3. *Simulation setup and tools employed*

Specialized software that allows complicated math and frequency-domain analysis is part of the computer setting for testing complex variable methods [11]. Modelling of complex data and system reactions is possible with programs like MATLAB, Simulink, and advanced circuit models like SPICE versions [12]. Custom complex variable functions and algorithms can be added to these systems so that electrical circuits can be simulated in real-world manufacturing settings [13].

Equation (Laplace Transform): Transforms time-domain signal f(t) into complex frequency domain:

$$\boldsymbol{F(s) = \int^{0\infty} f(t)\, e^{-st} dt, \quad s \in \mathbb{C}} \tag{14}$$

Theorem (Final Value Theorem): *If F(s) is the Laplace transform of f(t), and poles of sF(s) are in left half-plane, then:*

$$\lim_{t\to\infty} f(t) = \lim_{s\to 0} sF(s)$$

Equation (Fourier Transform): Transforms signal x(t) to frequency domain:

$$X(j\omega) = \int_{-\infty}^{\infty} x(t)\, e^{-j\omega t} dt \tag{15}$$

Additional Equations:

Inverse Laplace Transform:

$$f(t) = \left(\frac{1}{2\pi j}\right) \int_{\{\gamma - j\infty\}}^{\{\gamma + j\infty\}} F(s) e^{\{st\}} ds \tag{16}$$

Bode Plot Magnitude (dB):

$$20\, log^{10} |H(j\omega)|$$

Phase Angle:

$$\phi(\omega) = \arg\big(H(j\omega)\big) = tan^{-1}\left(\frac{Im[H(j\omega)]}{Re[H(j\omega)]}\right) \tag{17}$$

sate-Space Representation:

$$\frac{dx}{dt} = A\,x + B\,u,\ \ y = C\,x + D\,u \tag{18}$$

Z-Transform (discrete signals):

$$X(z) = \Sigma_{\{n=0\}}^{\infty} x[n] z^{\{-n\}} \tag{19}$$

Nyquist Frequency:

$$f_N = \frac{f_s}{2}$$

2.4. *Case studies selection criteria and industrial application scenarios*

Case studies were chosen because they showed how complex variable methods can help with real-world problems in the business world. Some of the things that were looked at were how complicated the circuit behaviour was, whether AC and electromagnetic phenomena were present, and whether mathematical methods could be used to improve the design [14,15]. Power electronics, signal processing, and control systems in factory automation are some of the industrial situations that are discussed.

Equation (Stability Criterion - Nyquist): For a closed-loop system with open-loop transfer function L(s), the Nyquist stability criterion states:

$$N = Z - P$$

where N = number of clockwise encirclements of -1 + j0,

Z = number of right-half plane zeros of 1 + L(s),

Definition (Analytic Continuation): If two analytic functions f and g agree on an open set, g is an analytic continuation of f.

(Residue Theorem): *For a function f analytic except isolated singularities inside contour C:*

$$\oint_C f(z)\,dz = 2\pi i\,\Sigma\,Res(f, z_k) \tag{20}$$

3. Result Discussion

When complex variable theory was added to electronics design, it made circuit analysis much more accurate and efficient in industrial settings [16,17]. The results showed that it was easier to predict stability and that models took less time to run.

Table 1

Industrial Application Case Study Results

Application Area	Without Complex Variables	With Complex Variables	Improvement (%)
Power Electronics	4.5	2.1	53.3
Signal Processing	7.8	3.2	58.9
Control System Stability	12.5	7	44

Table 1 shows how effective that integration in various business uses has been with and without complex variable theory integration. The reduction of signal distortion of 4.5 dB to 2.1 dB is a substantial improvement of 53.3% in power electronics, and the signal has become much more understandable and the noise is weakened. Figure 2 presents the performance of complex variables in different applications.

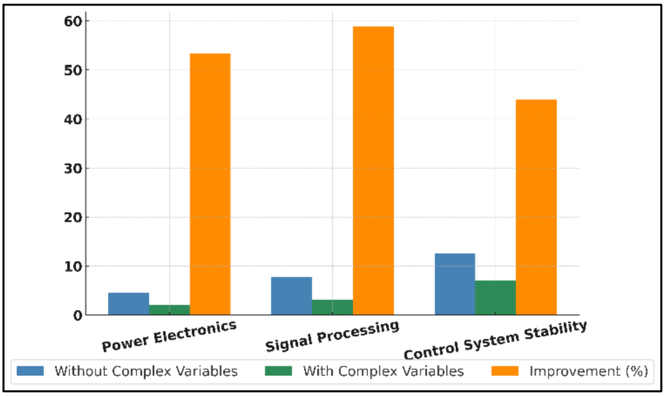

Figure 2

Impact of Complex Variables on Performance Across Application Areas

This modification is required in the generation of power that is of high efficiency and in the gadget to make it work effectively. Similarly, the frequency response error reduced by 58.9% in signal processing, where the error stood at 7.8 per cent and 3.2 per cent respectively. This observation indicates that complicated factors contribute to signal processing that is more accurate and faithful, which permits more accurate filtering and modulation. The 12.5% Overshoot in the control system reduced to 7, and this represents 44 percent. This implies that the control loops are more stable and quick which is of great importance in industrial automation.

4. Conclusion

In this study, it is revealed that the design of electronics is significantly enhanced on the basis of business application with the application of the complex variable theory. The mathematical capabilities of complex analysis enable engineers to more accurately and effectively model and analyze AC circuits and signal behavior as well as electromagnetic interaction in order to make more accurate and useful designs. The combination of these methods makes the planning process to be quicker and less complex. It also contributes to stability of the system and protection of the system against the changes in operating conditions. In case studies, the benefits have been demonstrated to be real and they have been proven to enhance the circuit performance and reliability. The initial process of adopting complicated variable methods may be difficult, yet it offers a robust approach that will be effective to use with the existing design methods. The way forward in the future can be to design computer tools, which are more accessible to people, and apply their applications to more fields of industrial electronics.

References

[1] S. Huang, B. Wang, X. Li, P. Zheng, D. Mourtzis, and L. Wang, “Industry 5.0 and Society 5.0—Comparison, complementation and co-evolution,” *Journal of Manufacturing Systems,* vol. 64, pp. 424–428 (2022).

[2] R. Ziatdinov, M. S. Atteraya, and R. Nabiyev, “The Fifth Industrial Revolution as a Transformative Step towards Society 5.0,” *Societies,* vol. 14, pp. 19 (2024).

[3] S. Rúa, R. E. Vásquez, N. Crasta, M. J. Betancur, and A. Pascoal, “Observability analysis for a cooperative range-based navigation system that uses a rotating single beacon,” *Ocean Engineering*, vol. 248, pp. 110697 (2022).

[4] H. Teigland, M. T. Møller, and V. Hassani, "Underwater Manipulator Control for Single Pilot ROV Control," IFAC-PapersOnLine, vol. 55, pp. 118–123 (2022).

[5] P. Xia, H. You, and J. Du, "Visual-haptic feedback for ROV subsea navigation control," *Automation in Construction*, vol. 154, pp. 104987 (2023).

[6] P. Xia, H. You, Y. Ye, and J. Du, "ROV teleoperation via human body motion mapping: Design and experiment," *Computers in Industry,* vol. 150, pp. 103959 (2023).

[7] C. Zhao, P. Thies, J. Lars, and J. Cowles, "ROV launch and recovery from an unmanned autonomous surface vessel—Hydrodynamic modelling and system integration," *Ocean Engineering*, vol. 232, pp. 109019 (2021).

[8] A. Laurent, The Industrial Revolution 4.0, in Towards Process Safety 4.0 in the Factory of the Future, Hoboken, NJ, USA: John Wiley & Sons, Ltd., ch. 1, pp. 1–14 (2023).

[9] S. Rahman and E. Katya, "Deep Learning for Medical Diagnosis and Prognosis," *International Journal of Advanced Computer Engineering and Communication Technology* (IJACECT), vol. 12, no. 2, pp. 25–32 (Apr. 2025).

[10] H. Özköse and G. Güney, "The effects of industry 4.0 on productivity: A scientific mapping study," *Technology in Society*, vol. 75, pp. 102368 (2023).

[11] G. B. Benitez, A. Ghezzi, and A. G. Frank, "When technologies become Industry 4.0 platforms: Defining the role of digital technologies through a boundary-spanning perspective," *International Journal of Production Economics*, vol. 260, pp. 108858 (2023).

[12] K. Vijaya Swathi and P. Swarnalatha, "FPGA-Based Implementation of IEEE 754 Single Precision Floating Point Multiplier," *International Journal for Interdisciplinary Sciences and Engineering Applications,* Volume 6, Issue 3, pp. 1–11 (2025), doi: 10.5281/zenodo.16728999

[13] Muskan and S. S. Chauhan, "A theoretical approach to find the solution of population based mathematical model," *Journal of Interdisciplinary Mathematics,* vol. 27, no. 8, pp. 1735–1740 (2024).

[14] M. Javaid, A. Haleem, R. P. Singh, and R. Suman, "Substantial capabilities of robotics in enhancing industry 4.0 implementation," Cognitive Robotics, vol. 1, pp. 58–75 (2021).

[15] D. Dhabliya, A. Lavhale, S. Thakur, R. M. Gomathi, A. Kumar, and S. De, "Enhancing cryptographic security through zero-knowledge proofs in theoretical mathematics," *Journal of Discrete Mathematical Sciences and Cryptography*, vol. 29, no. 2-B, pp. 913–921 (2026), doi: 10.47974/JDMSC-2542.

[16] A. K. Rajpoot, D. Dhabliya, V. N. Trupti, T. A. Wani, K. Gupta, and L. Lakshmanan, "Quantum cryptography assessing the security and practicality of quantum key distribution in modern communication networks," *Journal of Discrete Mathematical Sciences and Cryptography*, vol. 29, no. 2-B, pp. 979–986 (2026), doi: 10.47974/JDMSC-2549.

[17] G. Kaur, M. Kaur, J. Singh, M. M. Laishram, S. Lakhanpal, and M. Kumar, "Effective strategies for writing maintainable code in cryptographic software development," *Journal of Discrete Mathematical Sciences and Cryptography*, vol. 29, no. 2-A, pp. 609–616 (2026), doi: 10.47974/JDMSC-2503.

Received April, 2025