Journal of Robotics and Control (JRC)
Volume 5, Issue 5, 2024
ISSN: 2715-5072, DOI: 10.18196/jrc.v5i5.22408

# Design and Simulation of an Analog Robust Control for a Realistic Buck Converter Model

Ibrahim Khalaf Mohammed [1*], Laith Abduljabbar Khalaf [2]
[1] Department of Systems and Control Eng., College of Electronics Eng., Ninevah University, Mosul, Iraq
[2] Electrical Eng. Techniques Department, Technical Eng. College Mosul, Northern Technical University, Iraq
Email: [1] ibrahim.mohammed@uoninevah.edu.iq, [2] laith.abd@ntu.edu.iq
*Corresponding Author

*Abstract*—**The simplicity and cost of the control systems used in power converters are an urgent aspect. In this research, a simple and low cost voltage regulation system for a Buck converter system operating in uncertain conditions is provided. Using an electronic PID controller technique, the feedback control scheme of the presented Buck converter is carried out. Matlab software used a simulation environment for the proposed analog PID-based Buck converter scheme. The PID controller is easily implementable since it is built with basic and conventional electronic components like a resistor, capacitor and op-amp. The system simulation has high reliability as it is implemented using the Simscape package. The Simscape components used to build the converter system are modeled effectively taking into consideration including the practical factors such as internal resistance, tolerance and parasitic elements. This procedure certainly enhances the reliability of the simulation findings as the working conditions of the simulated system become more closer to the real-world conditions. Particle Swarm Optimization (PSO) is employed to properly optimize tune the PID gains. The regulation process of the PID control scheme is assessed under voltage and load disturbances in order to explore the robustness of the Buck converter performance. The findings from the system simulation, under the uncertainties, show largest rise time and settling time of 20 ms and 25 ms respectively, zero overshoot and minimum steady state error response, except at load disturbance case there is a fluctuation of 1 V. Consequently, It can be said that the proposed Buck converter based on analog PID controller can be used efficiently in the industrial and power applications.**

***Keywords*—*Proportional Integral Derivative; Buck converter; Optimization Algorithm; Particle Swarm Optimization; Voltage Regulation***

## I. INTRODUCTION

Switching modes electronic components known as DC-DC converters are frequently used in industrial applications, embedded systems, microprocessors, distributed power topologies and telecommunications [1]–[5]. Voltage converter systems are basically categorized into six types which are Buck, Boost, Sepic, Cuk, Zeta and Buck-Boost [6]. Buck DC-DC converters are among the switching mode power converters that are most widely employed in a variety of application domains because of their highly efficient power distribution, low cost, performance reliability and structural simplicity [7]–[9]. The appropriate output DC voltage may be generated using this conversion method, independent of changes in the supply voltage and load. An appropriate output DC voltage can be swiftly converted from the input DC voltage using a Buck converter. It is worth mentioning that variations in the supply voltage, desired voltage and load resistance may lead to uncertainties in a converter's ability to provide a steady output DC voltage. These uncertainties can lead to a performance loss and unstable output characteristics.

To achieve a precise voltage regulation and lessen the effects of these fluctuating problems, the converter should be used in combination with a suitable closed-loop control system. Many power engineers are interested in designing a Buck converter with a feedback voltage control system that can deliver a high precision and stable DC voltage for a variety of applications. Modern control techniques such as charge balance controller method [10], Linear Quadratic Regulator (LQR) [11], [12], Linear Quadratic Gaussian (LQG) [13], Pole Placement (PP) [14], Sliding Mode Control (SMC) [15]-[19], Back Stepping Control (BSC) [20], Bang-Bang Control (BBC) based on geometric approach [21], Neural Network Predictive Controller (NNPC) [22], Robust Control (RC) [8], [23], Adaptive Control (AC) [24] and Hybrid Control (HC) [25] have been presented to improve the voltage adjustment behavior of the Buck converters. However, PID controller methodology is still the most popular and efficient solution can be considered for Buck converters control and many industrial applications due to the simplicity of its implementation in both software and hardware domains [26]–[29].

The study of adopting classic PID control strategy for Buck converters remains a topic of interest among researchers. The authors in [24] presented a voltage regulation system for Buck converter with disturbances based on classic and modified control approach. They introduced conventional and adaptive voltage-model control for a switching DC-DC converter. The proposed system uses two-loop classic regulator for control and

Identify applicable funding agency here. If none, delete this.

stable the output of Buck converter. The introduced system presents less noise problems while giving more robust and stable response. The system utilizes two loops based on three controllers, an inner adaptive loop with double controllers and an outer voltage control loop with single controller. The outer loop preserves the loop bandwidth and stability margins under a large variation of the supply voltage and tolerance of passive elements of the converter, in addition to improving the disturbance rejection of the closed loops of the system. The proposed system is implemented in the real-time and its experimental results are presented and then compared with those of the traditional single loop system.

In [30] a new formulation of PID control technique is proposed to improve the performance of DC-DC converter schemes. The derivative term associated with the PID controller is utilized to inject an output voltage with a significant noise in DC power converter systems. In the new PID formulation the output-voltage derivative is replaced by information about capacitor current, hence reducing noise injection. The obtained results showed that the proposed model is active for a current-mode controlled Boost converter and voltage-mode controlled Buck converter with PID feedback control system. Two digital feedback controllers for DC-DC power converter based on PID technique are introduced in [31]. A digital multi-loop PID controller has been implemented, whose design based on the proposed loop shaping of the frequency-domain transfer function. This work presents also design and implementation of a digital LQG state-feedback controller based on a time-domain state-space model of the same proposed converter topology that has been presented.

In [32] a Field-Programmable Gate Array (FPGA) device has been employed to implement both the PID controller and the Generalized Proportional Integral (GPI) controller for the Buck converter system. The implementation results of the converter based on the controllers were presented and then compared. The comparison results showed that the GPI controller exhibits a larger degree of robustness in terms of turbulence rejection based on extreme changes in static and dynamic loads compared to the classic PID controller technique. Moreover, the GPI controller can introduce a superior response compared to the classic PID controller regarding the settling time parameter.

In 2021, the authors proposed an optimization method for PID controller used in Buck converter system [33]. The optimization method is based on extreme Learning Machine (ELM) approach, which is used to achieve an online adjustment for the controller gains coefficients. The combination of ELM with PID control is employed to perform a voltage adjustment for the Buck voltage regulator. The ELM-PID control scheme is designed and simulated in the MATLAB/Simscape toolbox to assess the capability of the introduced controller to stabilize the output of the Buck voltage regulator under different working disturbances. In this study, the voltage adjustment of the ELM-PID controller is compared with that of the open-loop control strategy to reveal the effectiveness of the combined ELM-PID controller.

Additionally, for applications involving Buck and Buck-Boost converters, the authors in [34] compared the control efficacy of fuzzy and digital PID controllers. The authors were made a comparison between the two control systems based on design methodology and their voltage regulation performance. The outputs of the converters using these classic controller techniques are presented and analyzed based on the time-domain performance parameters. However, instead of adopting numerical optimization algorithms to determine the values of control elements for the controllers, the researchers in this work tuned the parameters of the controllers manually utilizing the traditional trial and error method.

In 2023, a new control approach is presented in [35] for step-down Buck converter system. The author used time-based PID controller as an alternative control style used to regulate and track the desired voltage of Buck converter. All the parts of the PID controller (Proportional, Integral and Derivative) are fully integrated in the time-domain. The Buck voltage regulator with the PID control is formulated mathematically and analysed in the time-domain. The Buck voltage regulator with the new PID structure is simulated to evaluate the voltage regulation of the introduced control system. However, the presented scheme is not tested in the presence of the parametric uncertainties and load variations of the converter.

This study presents a conventional controller method to maintain the desired output voltage of Buck converters under different operational disturbances taking into consideration overcoming the aforementioned problems. The feedback control system for the proposed DC-DC Buck regulator under hard working disturbances is implemented using a PID controller. Generally, in design of control systems, the setup of the gain parameters for Buck converter controllers is typically the largest challenge. In most controllers in use now, the controller gains are optimized manually utilizing the trial and error adjusting method, which requires more time and effort, in addition, there is no guarantee that this gain setting approach will lead to the best performance [36]. There is no assurance that this will lead to the best performance. Therefore, it is necessary to carefully adjust the controller settings in order to manage the voltage regulation process of DC-DC Buck converters and provide the demanded output response.

In [37]–[39] the performance of the voltage-mode Buck converters was enhanced by using conventional tuning procedures. The authors used traditional frequency response approaches including Ziegler-Nichols and root locus-type methods to find optimum values of gain parameters for feedback control system. Unfortunately, early convergence or extended computation times make the typical methodologies offered insufficient for specific solution procedures. To solve these problems, optimization algorithms, which are implemented using numerical techniques, are adopted to achieve a global solution for control problems under certain restrictions, hence, finding best values for controller parameters.

Over the past few decades, a variety of intelligent optimization techniques, such as Fuzzy Logic (FL) [40], Genetic Algorithm (GA) [41], [42], Particle Swarm Optimization (PSO) algorithm [43], [44], Bacterial Foraging Optimization (BFO) algorithm [45], [46], Big Bang-Big Crunch (BBBC) algorithm [1], Aquila Optimizer (AO), African Vultures Optimization Algorithm (AVOA) and Hunger Gamnes Search optimization (HGSO) algorithms [47] [48] and Bat Algorithm (BA) [49] have been utilized to successfully optimize the performance of the introduced PID controlled Buck converters. Unfortunately, the implementation of some of these optimization algorithms has severe flaws and limitations. Complex dynamical systems cannot be optimized using the GA method since the optimization process of these systems using the GA method needs large numbers of iterations and in addition to the problem of early convergence. Utilizing the BFO tuning method to tackle unconstraint systems may result in a local solution rather than a global solution due to some problems related to the execution of the algorithm like limitation of chemical step size and weak bacterial interactions. Concerning the BBBC tuning approach, its implementation process includes some flaws for instance slow convergence and a propensity to become trapped at a local optimal solution. PSO algorithm is adopted by many researchers to achieve optimization process of the control system in Buck converters due to its simple concept, fast convergence and the ability to meet a global solution for control problems [50], [51].

The researchers in [44] presented a digital PID control scheme for feedback loop of step-down Buck converter. This work offers an alternate method of parameter determination for PID controllers. The setting of the PID parameters is achieved using four different PSO formulations, which are Direct (traditional) PSO (D-PSO), Cazy PSO (C-PSO), Constriction-Factor PSO (CF-PSO) and Inertia Weight PSO (IW-PSO). To verify the tuned PSO-PID controller, the optimized Buck converter system is implemented in the real-time domain. The performance of the hardware Buck circuit based on tuned PSO-PID controller is assessed under load and line voltage variation conditions. The experimental results of the system are presented and analyzed based on transient and steady state performance parameters. The application results demonstrate the CF-PSO algorithm has the best tuning performance for PID gain parameters compared with that of other modified PSO algorithms.

Anjan et al. proposed a control method to improve transient response and reduce the steady state error of Buck output voltage [52]. They presented optimal PID controller design for DC-DC Buck converter system. The selection of the PID gains coefficients is achieved utilizing the PSO algorithm. In this study, the authors used a classic PID controller with Low Pass Filter (LPF) to reject the high frequency signals and clamping control approach to address up the wind-up issue of integral controller. The PID controller with the anti-windup control technique is simulated using MATLAB/Simulink environment. Four fitness functions are adopted in the PSO algorithm. The proposed system is verified based on input voltage and load fluctuation. The Simulink results of the converter under disturbances are presented to assess the behavior of the proposed control system.

In 2023, the authors in [53] proposed an analog PI controller in the feedback control system to decrease the input voltage of Buck converter to 50%. The voltage adjustment action of the introduced converter with the analog PI controller is further compared with the digital PI based-Buck converter. The simulation results demonstrate the capability of the simple analog PI controller in improvement the stability and accuracy of the proposed converter. However, the performance of the presented system is not investigated in the presence of turbulence of voltage and load.

All the studies presented in the literature review proofed activity of classic type PID controller in regulation process of the Buck converter output. However, these studies include many drawbacks regarding reliability, implementation complexity, control optimization and test conditions. In some of the presented Buck converter systems above, a standard PID Simulink block is used to construct the feedback control system for the converters that in fact is not realistic model. In addition, digital implementation of the PID control algorithm in the real-time domain is not easy to realize as it needs a programmer device to program the electronic board (Arduino, microcontroller, etc). Furthermore, the regulation performance of the presented PID controllers is not evaluated under hard working conditions like voltage disturbances and varying load. Moreover, in some of the introduced works, the controller parameters are not set properly using numerical optimization techniques.

This study contributes to presenting a reliable trustworthy converter model that effectively overcomes all the design and implementation flaws mentioned above. The simulation model of the proposed Buck converter system that is presented in this article is close to reality and is practically implementable because it was built using elements after considering all the factors that support its realistic representation, such as parasitic capacitors, permittivity, tolerance and internal impedances. In addition, an easily implementable and simple structure control system is adopted in the feedback path of the converter using an electronic model PID controller. The use of analog PID controllers for voltage regulation task in converters has been supported by the current developments in the manufacture of electronic devices and operational amplifiers. The electronic PID controller can be simply constructed by analog components from the Matlab/Simscape, which considers more reliable simulation environment compared to the Matlab/Simulink toolbox

[54].

PSO tuning method is utilized for allocating best values for the PID gain coefficients. For the sake of performance evaluation for the introduced conversion system, the Buck voltage regulator with the PSO-PID control is simulated utilizing the MATLAB/Simscape environment. In this article, five hard working circumstances, load disturbance and variations in the supply voltage and desired voltage, are considered to examine the robustness of the suggested PID controller technique.

Rest of the research paper is embodied as follows; Section II introduces structure identification and dynamic modeling of Buck power converter. Then in section III, technique of PID controller used in the converter system is illustrated. Implementation of the proposed electronic PID controller is shown in section IV. Optimization method of the controller is presented in section V. Thereafter, design and implementation of the PID controlled Buck converter system are explained in section VI. Findings from the system simulation are presented and analysed in section VII. Finally, conclusive remark and future works are given in section VIII.

## II. BUCK IDENTIFICATION AND MODELING

### A. System Structure and Configuration

Buck converter is a voltage-mode power regulation system. It is normally called a step-down converter as it provides the load by an output voltage lower than its input voltage. Fig. 1 depicts the electrical circuit of a conventional Buck converter.

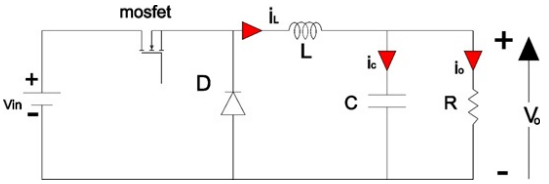

Fig. 1. Block diagram of Buck electric circuit

The converter circuit is mainly composed of the following components:
**IGBT transistor**. It is employed a power switch device that is controlled by a command signal provided externally by a control circuit. The use of this device in this study enhances the reliability of the proposed converter as its switching performance is more efficient at high frequency applications compared with MOSFET transistor. In addition, this switching device can operate at zero-voltage case through OFF state, hence decreasing the power losses of the converter system [55], [56].
**Filter capacitor (C)**. It is an electric charge storage unit. The main function of the capacitor is to minimize the overshoot and the ripples at the voltage signal across the load.
**Inductor (L)**. This electrical element serves a storage energy unit in the converter circuit. It performs as a voltage source used to supply DC-voltage to the load as soon as transistor is in OFF state.
**Free-wheeling diode (D)**. It is used to provide an outlet through which the inductance current passes through the load once the transistor is opened.
**Load**. It is any appliance, which in this study is considered a resistance element connected across the Buck regulator output.

The presence of inductor and capacitor elements in the circuit makes the Buck converter a nonlinear system as these elements are used to store energy and their voltage-current relationships are nonlinear and differential. [57], [58]. The diode in the Buck circuit performs as a controllable switch by which the power can flow in two directions between input and output of the converter.

In the converter circuit, the current continues to flow through the load even the power IGBT switch is in cut OFF state, the source of the current is from the inductor device, which acts as an energy storage unit. The filter capacitor device is used to reject the noise and lessen the voltage ripple in the output signal of the converter. The Buck converter is working based on a switching time period (T) with duty cycle ($d$). It is important to keep in mind that the converter behaves non-linearly since it incorporates an inductor and capacitor devices. The State Space Averaging (SSA) technique is a popular method used to linearize the Buck system and formulate its general model based on both switching modes.

### B. System Modeling

It is assumed in this study that the Buck converter operates in the Continuous Conduction Mode (CCM) and that every component in its circuit is ideal. In this working mode, the inductor's current passes continuously with low ripple value through the converter circuit during the full period time (T) [59], [60].

The operation of the Buck converter system is governed by the switching state of the power transistor. As a result, two electrical circuits are taken into account, one for the ON state and the other for the OFF state of the transistor.

#### 1) Converter Switching States

**Switch ON case**. In this working case, the IGBT transistor is switched ON and the diode behaves as an open circuit as it is reverse biased. The voltage supply of the converter is connected with the stored power inductor and the resistive load. The inductor' s current in the converter circuit passes through the IGBT device going to the load. Fig. 2 depicts the schematic diagram of the converter circuit based on the switch ON mode. During the period of this switching state, $0 < T_{on} < d$, using Kirchhoff's rules the inductor's voltage is derived as follows:

$$L\frac{di_L(t)}{dt} = V_{in} - V_o \tag{1}$$

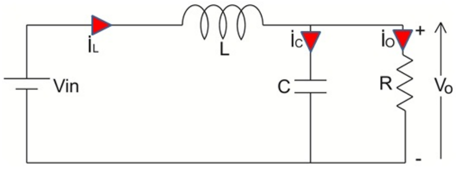

Fig. 2. Buck electric circuit converter at ON switch mode

while the capacitor's current is given by the following expression:

$$C\frac{dV_c(t)}{dt} = i_L(t) - i_o(t) \tag{2}$$

The mathematical representation of the Buck converter should be formulated in a state space representation. The reason for this is that the state space model of the converter is very easy to simulate and analyze in the Matlab/Simulink environment compared to the circuitry model. In addition, running the optimization algorithm of the control scheme utilizing the Buck state space model is faster compared to the circuitry model.

The inductor current and capacitor voltage are the state variables of the converter system. The state vector of system is assumed as follows: $x(t) = [x_1(t) \;\; x_2(t)]^T = [i_L(t) \;\; V_c(t)]^T$. The supplied voltage to the converter is regarded the control effort of the Buck system, $u(t) = V_{in}(t)$. State space representation is adopted to describe the time-variant buck converter system in form of linear state matrix model. Using (1) and (2), the state and output equations that formulate the state space representation of the Buck system based on switch ON mode are given below:

$$\begin{bmatrix} \dot{i}_L(t) \\ \dot{V}_c(t) \end{bmatrix} = A_1 \begin{bmatrix} i_L(t) \\ V_c(t) \end{bmatrix} + B_1 u(t) \tag{3}$$

$$y(t) = C_1 \begin{bmatrix} i_L(t) \\ V_c(t) \end{bmatrix} \tag{4}$$

where $A_1 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & \frac{1}{RC} \end{bmatrix}$, $B_1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$ and $C_1 = \begin{bmatrix} 0 & 1 \end{bmatrix}$

**<u>Switch OFF state</u>**. As shown in Fig. 3, when the switch is in OFF position, the freewheeling diode creates a way for the load resistor to serve as a conduit to release the stored energy in the inductor.

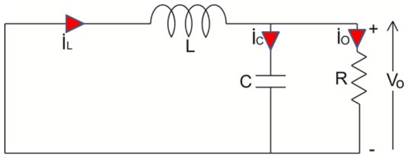

Fig. 3. Buck electric circuit at OFF switch mode

In this operational mode, $d < T_{off} < T$, utilizing Kirchhoff's current and voltage laws, (5) and (6), respectively, provide the system's inductor current and capacitor voltage.

$$\frac{di_L(t)}{dt} = -\frac{V_c(t)}{L} \tag{5}$$

$$\frac{dV_c(t)}{dt} = \frac{i_L(t)}{C} - \frac{V_c(t)}{RC} \tag{6}$$

Using (5) and (6), the state space formulation including state equation and output equation of the Buck voltage regulator is given as follows:

$$\begin{bmatrix} \dot{i}_L(t) \\ \dot{V}_c(t) \end{bmatrix} = A_2 \begin{bmatrix} i_L(t) \\ V_c(t) \end{bmatrix} + B_2 u(t) \tag{7}$$

$$y(t) = C_2 \begin{bmatrix} i_L(t) \\ V_c(t) \end{bmatrix} \tag{8}$$

where $A_2 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & \frac{1}{RC} \end{bmatrix}$, $B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$ and $C_2 = \begin{bmatrix} 0 & 1 \end{bmatrix}$

### 2) *State Space Averaging (SSA)*

The state space averaging technique is a powerful method for formulating the modeling of non-linear systems. This approach uses duty cycle of the transistor control signal to average the state and output equations for ON and OFF switched circuits and formulating a linear first order state differential equation. The averaged state and output equations are used in designing the feedback control scheme of Buck converters [61]. Using (3), (7) and (8), the general state equation and output equation of the Buck voltage regulator system are given below in (9) and (10) respectively.

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{9}$$

$$y(t) = Cx(t) + Du(t) \tag{10}$$

where $A = dA_1 + (1-d)A_2 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}$, $B = dB_1 + (1-d)B_2 = \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix}$, $C = dC_1 + (1-d)C_2 = \begin{bmatrix} 0 & 1 \end{bmatrix}$ and $D = 0$. The duty cycle of the converter system is given below:

$$d = \frac{V_o}{V_{in}} \tag{11}$$

The Laplace transform of (11) is used to determine the transfer function of the step-down chopper system with respect to the source voltage.

$$\frac{V_o(s)}{V_{in}(s)} = C(sI - A)^{-1}B + D \tag{12}$$

Using (9) and (10), the final formula of the transfer function for the Buck converter based on the duty cycle element is given below:

$$\frac{V_o(s)}{d} = \frac{\frac{V_{in}}{LC}}{s^2 + \frac{1}{RC}s + \frac{1}{LC}} \tag{13}$$

## III. CONTROLLER TECHNIQUE

In this article, a PID controller is employed to control the output voltage of the Buck regulator. The PID controller is still the most widely utilized control method in industrial engineering, despite ongoing developments in modern control approaches throughout time. This is due to its easy to realize in practice and uncomplicated structure, in addition to its ability to deliver adequate, dependable performance under various control-related conditions. The reason for that belongs to the fact that its control action is formulated using proportional, integral and differential parts that deals actively with previous, current and future response of the system respectively. The s-domain transfer function formula of the PID controller is given below:

$$\frac{U(s)}{E(s)} = \frac{K_d s^2 + K_p s + K_i}{s} \tag{14}$$

where U(s)and E(s) are the PID command signal and difference between the reference signal and the converter's output voltage in the s-domain respectively and $K_p, K_i, K_d$ indicate the proportional, integral and derivative coefficients of the PID controller respectively.

## IV. ELECTRONIC PID IMPLEMENTATION

In this study, a simple implementation approach is utilized to realize the feedback PID control system for the Buck voltage regulator circuit. The implementation of the proposed PID controller parts is achieved by using analog electronic elements from the Simscape library.

**Proportional term**. The electronic circuit of the PID proportional part is shown in Fig. 4. It is basically a simple inverting amplifier circuit that performs amplification for the error input signal. This controller parameter deals with the present error input of the system. The proportional gain element is set based on the values of the input resistance ($R_1$) and feedback resistance ($R_2$) through the expression: $K_p = R_2/R_1$.

**Integral term**. Fig. 4 shows the analogue structure of the PID integral term. This controller gain parameter accumulates errors of the system response over time and helps eliminate stationary errors. It acts as a correction factor, so that it can adjust the control signal based on the accumulated error. A higher Ki results in a stronger correction and reduce the steady state error, but it can also cause the system to become sluggish or unstable. The Integral gain element is calculated using the expression: $K_i = 1/R_3C_1$, where ($R_3$) is the input resistance and ($C_1$) is feedback capacitance.

**Derivative term**. The derivative part of the PID controller implemented using electronic components is shown in Fig. 4. This parameter measures the rate of change of error signal in the control system. Based on this measurement, the correction performance of the gain parameter is achieved. $K_d$ gain parameter acts as a damping factor by which it can reduce overshoot and improve the response time of the controlled system.

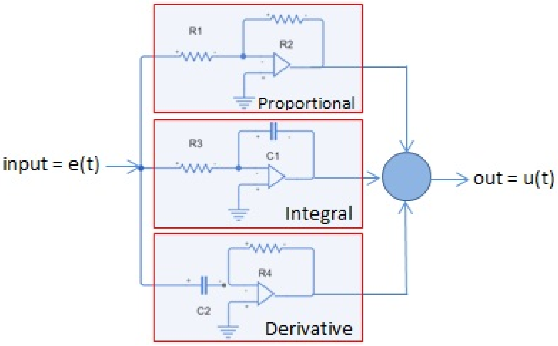

Fig. 4. Electronic circuit of PID control terms

Increasing the setting value of the derivative parameter rises attenuation process of the control system, limits the overshoot of the response and also improves the settling time. However, this action can also increase the system noise. For that, a trade off between performance elements should be considered in the setting process of the $K_d$ parameter. The derivative gain parameter of the controller can be determined using the expression: $K_d = R_4C_2$. Set the input capacitance $C_2$ and feedback resistance $R_4$ in a high value can limit the overshoot of the response and also improve the settling time. As a result, proper tuning of PID gain parameters enables the controller to provide a suitable control signal that can regulate the output signal of the converter properly and maintain it stable at the desired value.

## V. PSO ALGORITHM

In this article, PSO algorithm is utilized to perform tuning process of the controller coefficients utilized in the proposed step-down converter. PSO is a kind of swarm-based stochastic intelligence algorithm that has the benefits of basic algorithm theory, easy programming and fewer programmable parameters. The algorithm's main idea is to create a swarm of randomly distributed particles that roam the problem space in search of the optimum location that best suits their requirements as determined by a cost function at each iteration [43].

At every iteration, throughout the searching task of each particle, obtaining a new place is influenced by two different factors: the first is the best experience the particle has had up to that iteration and the second is the best experience of all the particles combined. The place of particle obtained represents the suggested solution of the control problem, each solution gives vector of the problem variables $[k_1k_2...k_m]$, where $m$ is the dimension of the problem variables. $p_{best}$ refers to the particle's best position that was discovered at each iteration. while the best place of all particles is denoted by $g_{best}$. Fig. 5 shows particles movements within the solution space. By using the previous best personal position $p_{best}$ and best solution of entire population group $g_{best}$, the place, which represents solution, and velocity of each individual particle are updated using (15) and (16) respectively.

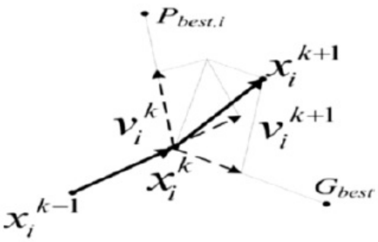

Fig. 5. Movement of PSO particles in search space

$$X_i^{k+1} = X_i^k + V_i^k \tag{15}$$

$$V_i^{k+1} = w.V_i^k + c_{r_1}^k(p_{best}6k - x_i^k) + c_{r_2}^k(p_{gest}6k - x_i^k) \tag{16}$$

where, $i = 1, 2, \ldots, N_p, N_p$ is the size of algorithm population, $k = 1, 2, \ldots, k_{max}, k_{max}$ is the maximum number of algorithm iterations, $V_i^k$ is the velocity of the $i^{th}$ bird, $w_1$ is the coefficient of inertial weight $c_1$ and $c_2$ are the learning factors, which represent cognition and social weight respectively, $r_1$ and $r_2$ are random numbers between [0,1], $X_i^k$ is the $i^{th}$ bird place.

In this work, the PSO tuning method is utilized to obtain best values for the PID gain elements $K_p, K_i$ and $K_d$. It is worth mentioning that the effectiveness in obtaining optimal PID gains depends on the choice of the objective function and parameters of the used optimization algorithm. The implementation process of the algorithm bases on the concept of minimization of the objective function, which should be formulated based of the required performance parameters. The index function considered in this work is not chosen from the standard performance indices, which deal with error parameter only. The proposed objective function is efficiently formulated to include the transient and steady state response parameters. This will certainly support the efficiency and reliability of the optimization algorithm. The objective function is given below:

$$f = a_1 M_O + a_2 t_r + a_3 t_s + a_4 e_{ss} \tag{17}$$

where $a_1, a_2, a_3$ and $a_4$ are weight of maximum overshoot, rise time, settling time and steady state error performance parameters. The values of these performance weights are set according to the desired output response: $a_1$ is $20\%$ peak overshoot, $a_2$ is $20\%$ rise time, $a_3$ is $30\%$ settling time and $a_4$ is $30\%$ steady state error. Fig. 6 depicts the flowchart diagram of the PSO algorithm for the Buck control problem.

## VI. CONTROL STRUCTURE AND IMPLEMENTATION

A voltage mode Buck converter is employed to supply the load with the required DC output voltage. Fig. 7 depicts the schematic diagram of the closed-loop voltage control system for the Buck converter system. PID controller technique is utilized to implement the feedback voltage adjustment system of Buck regulator with disturbances. In this research, the command signal from the PID controller is utilized to generate an adjustable duty cycle Puls Width Modulation (PWM) control signal. This PWM command signal is employed to drive the Buck switching device, hence, control the level of its output signal.

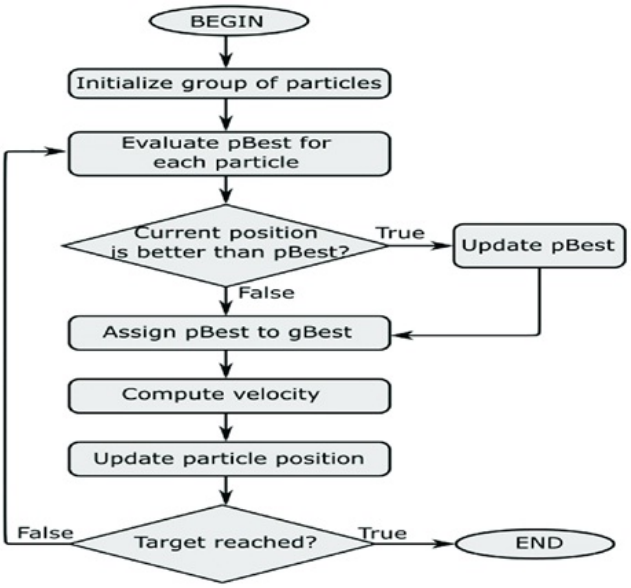

Fig. 6. Flowchart of the PSO tuning algorithm

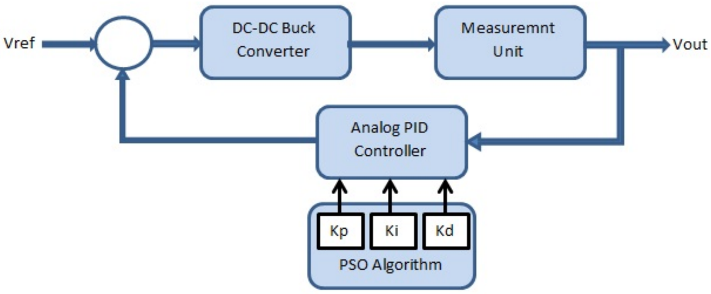

Fig. 7. Block diagram of the PSO-PID based Buck converter system

The Buck regulator circuit is designed based on specific performance requirements. Table I lists the electrical parameters and circuit components of the proposed Buck regulator system. The converter is designed using [62] to provide a resistive load by a power of 20 W and output voltage of 5 V, hence duty cycle $d$ of 0.4167, with a current ripple $\Delta i_o$ and voltage ripple $\Delta V_{out}$ of 4% and 2.5% respectively.

In the implementation process of the control system, a fine tune for the controller parameters, $K_p, K_i$ and $K_d$ is achieved using PSO optimization algorithm. In the simulation procedure of the proposed system, the implementation code of the PSO

TABLE I. PARAMETERS OF BUCK CONVERTER

| Parameter name | Symbol | Value | Unit |
|---|---|---|---|
| Source voltage | $V_{in}$ | 12 | V |
| Resistance | R | 1.25 | Ω |
| Capacitance | C | 200 | $\mu$F |
| Inductance | L | 72.9 | mH |
| Switching frequency | $F_s$ | 1000 | Hz |

algorithm based on the parameters listed in Table II is initially executed in a Matlab script file (m-file). The Simulink model of the Buck regulator system is then called from the script file using the Matlab "Sim" command to run the simulations syntactically.

TABLE II. PARAMETERS OF THE PSO ALGORITHM

| Parameter Name | Symbol | Value |
|---|---|---|
| Population volume | p | 50 |
| Iteration number | k | 100 |
| Cognitive component | $c_1$ | 1.3 |
| Social component | $c_2$ | 1.3 |
| Maximum speed | S | 10 |
| Maximum iteration weight | $w_{max}$ | 0.7 |
| Minimum iteration weight | $w_{min}$ | 0.4 |

The controller parameters of the feedback control system continue to be updated through this interaction between the two Matlab environments until the best gain parameters are obtained. The optimum values of the PID controller elements obtained are, $K_p = 58.33, K_i = 1.75$ and $K_d = 1.45e-6$. It is worth noting that these gain parameters will be adopted in all the suggested system working scenarios presented in the next section.

The circuits of the PID proportional, integral and derivative gain parameters are realized using resistors, capacitors and op-amps devices. Based on the optimized PID gain parameters, the analog circuits components of the controller coefficients are calculated using the mathematical expressions stated in the previous section. In the design of the proportional term circuit, the input resistance ($R_1$) is chosen 1 kΩ and the feedback resistance ($R_2$) 58.33 kΩ is determined using the previously mentioned expression $K_p = R_2/R_1$ based on the optimized $K_p$ 58.33. Table III lists the electrical components values of the proportional, integral and derivative circuits and resistance values of PWM drive circuit for the IGBT device. The gain parameters of the controller are carefully adjusted in this study using the PSO optimization algorithm.

The ability of the step-down DC-DC converter to regulate the voltage signal across its load element is evaluated based on five working scenarios: disturbances in input voltage, reference voltage and load resistance. This is done in order to verify the robustness of the proposed PID controller system in tracking process for the reference trajectories. An examination of the controller robustness was carried out by analyzing the system performance based on the transient and steady state response factors: rise and fall time, arrival time, peak overshoot and steady state error.

TABLE III. ANALOG COMPONENT VALUES OF PID PARAMETERS AND DRIVE CIRCUIT

| Parameter Name | Symbol | Value | Unit |
|---|---|---|---|
| $K_p$ Resistance1 | $R_1$ | 1 | kΩ |
| $K_p$ Resistance2 | $R_2$ | 58.33 | kΩ |
| $K_i$ Resistance | $R_3$ | 121.5 | kΩ |
| $K_i$ Capacitance | $C_1$ | 4.7 | $\mu$F |
| $K_d$ Resistance | $R_4$ | 1 | kΩ |
| $K_d$ Capacitance | $C_2$ | 1.45 | nF |
| PWM Resistance1 | $R_5 - R_{11}$ | 100 | kΩ |
| PWM Resistance2 | $R_{12}$ | 3.4 | kΩ |

The controller is designed to deliver a stable voltage range (2-10) V across a varying resistive load (0.5-3)Ω of the converter based on changing supply voltage (8-24) V. The values of the gain terms $(K_p, K_i, K_d)$ for the electronic PID control system are optimized efficiently utilizing the PSO method. During the implementation of the tuning approach, the process of minimizing the cost function continues until the converter shows the required output response, which are $t_r = 0.1s, M_o = 10\%, t_s = 0.7s$ and $e_{ss} = 0.02$ V.

## VII. SIMULATION RESULTS AND DISCUSSION

The MATLAB software is used in this work to model and simulate the proposed Buck system. For the sake of supporting the realism of the Buck system and enhancing the reliability of the proposed PID analog controller, Simscape toolbox is adopted to create, simulate and evaluate the model of the proposed system. Fig. 8 depicts the Simscape model of the suggested power system.

**Scenario I: Fixed input and output voltage**. The source and reference voltages of the Buck converter scheme are chosen in this scenario 12 V and 5 V, respectively. During this operation case the proportional, integral and derivative coefficients of the PID controller as mentioned before are tuned properly utilizing the PSO method. Fig. 9 displays the output signal of the regulator system based on the optimized PID parameters mentioned previously. From the converter response, it can be seen that the feedback control scheme using the PSO-PID controller was successful produced a precise and stable voltage signal across the load's terminals of the converter. The output waveform showed a rising time of 22 ms, settling time of 25 ms, peak overshoot of 2% and steady state fluctuation is within roughly the desired oscillation value that was considered in the scheme design specifications.

**Scenario II: Input voltage disturbance**. In this operation scenario, the input voltage of the converter is adjusted in the sequence (8-12-18-24) V with a change time of 1s, while the desired voltage value is set to 5V. Fig. 10 shows the time response of the output voltage signal for the power converter

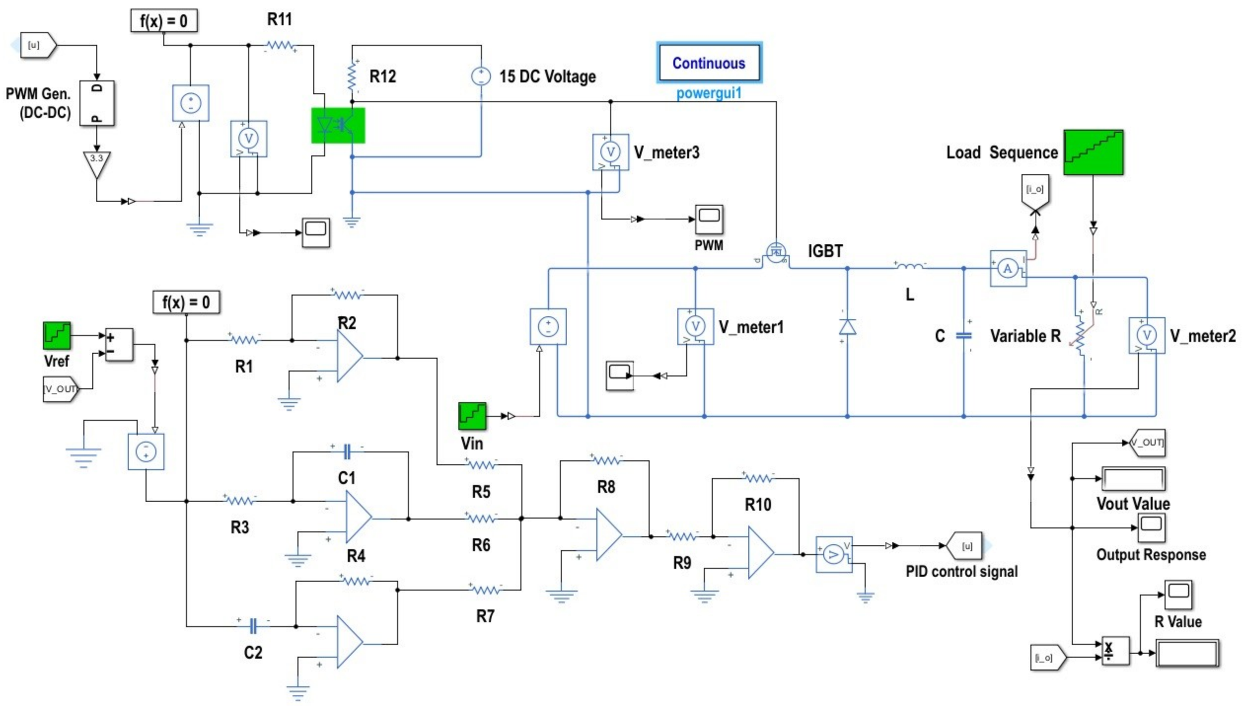

Fig. 8. Simscape schematic diagram of the Buck converter with feedback PID controller

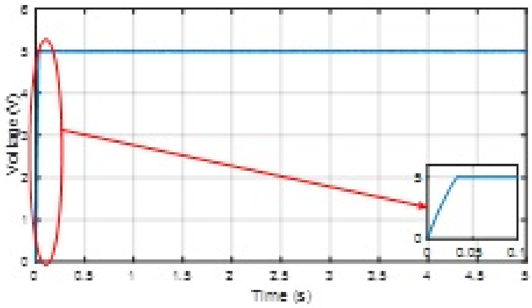

Fig. 9. Buck output based on constant source and desired voltages

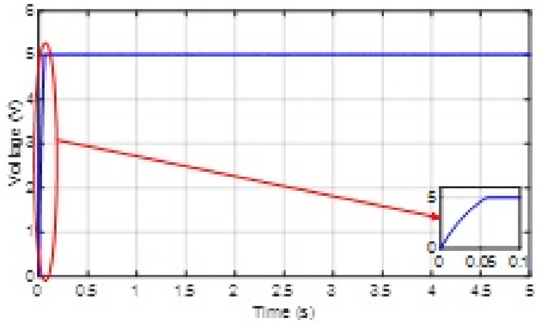

Fig. 10. Buck output based on varying source voltage

system based on the same PID controller gain parameters stated previously. From the mini-plot of Fig. 10, it can be said that despite input voltage uncertainties, the regulated Buck converter was able to successfully deliver an accurate and constant DC voltage to the resistive load. The system's output response showed a rising time of 0.045s, zero overshoot and small swinging around the demanded voltage ripple value.

**Scenario III: Desired voltage disturbance**. During this disturbance state, the step-down DC-DC regulator is powered by a constant voltage of 12 V and its response is evaluated under varying demand voltage sequence (4,6,8,10) V with a change time of 1s. Fig. 11 depicts the converter's output voltage under reference voltage disturbance. It can be noted from system response that the optimizing PSO-PID controller guided the regulator's output through the trajectory of the changing desired voltage efficiently. At initial step of the desired voltage (4V), the rising time of the converter output is approximately 20 ms and for the other reference steps the rising time is slightly increased to 30ms, which is considered an acceptable and reasonable value. The overshoot and oscillation values of the converter response over the whole reference value range are roughly zero.

**Scenario IV: Load disturbance**. In this working case, the voltage regulator is evaluated based on variable resistive load under 12 V supply voltage and 5 V desired voltage. Fig. 12 and 13 show smooth variation of resistive load and output voltage response of the step-down DC-DC converter respectively. It

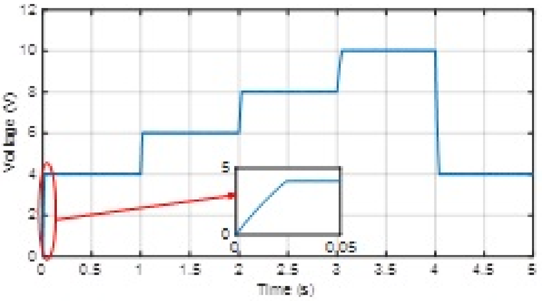

Fig. 11. Output response of Buck converter based on varying reference voltage

is obvious from Fig. 13 that despite of the changing in the load resistance value, the optimized proportional, integral and derivative gain parameters of the PID control system enabled the converter to supply the load efficiently with an accurate and stable DC voltage signal.

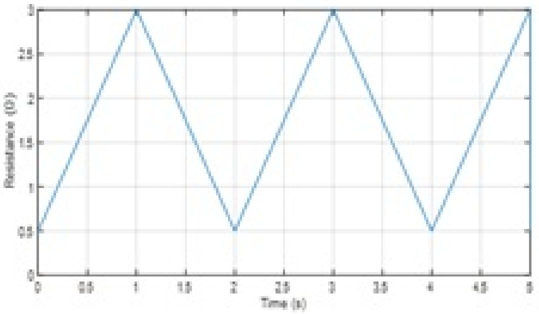

Fig. 12. Smooth variation of load resistance for Buck converter

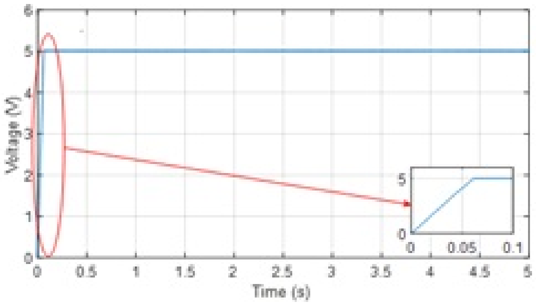

Fig. 13. Buck output response based on smooth varying resistive load

In this study, further hard disturbance in load resistance is considered in robustness test of the proposed converter system. Under a sudden change in load resistive shown in Fig. 14, the output response of the PSO-PID based Buck converter is illustrated in Fig. 15. The simulated response of the system demonstrated the robustness of the presented controller through its ability to force the regulator output to effectively track the demanded voltage trajectory despite a sharp change in the resistance. The system showed a fast transient response (17 ms rise time, 21 ms settling time) and minimal steady-state error. However, there are overshoots appeared at the resistance change times, which have been decreased significantly with increasing time.

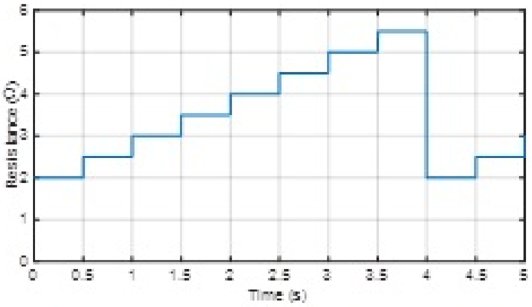

Fig. 14. Sharp change sequence of resistive load of Buck converter

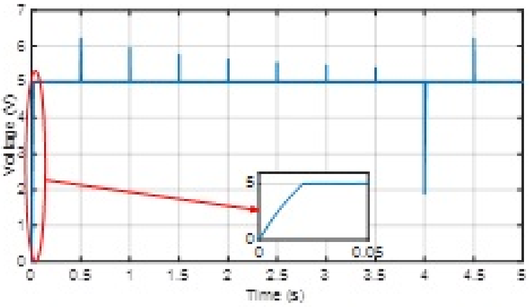

Fig. 15. Output response of Buck converter based on sharp changing resistive load

**Scenario V: Supply, reference and load disturbance**. In this working circumstance, an additional hard test is taken into account in the investigation process of the durability of the proposed system. The voltage adjustment robustness of the proposed converter is examined based on uncertainties conditions of load, source voltage and desired voltage. The performance of the controller in tracking the path of the desired reference voltage (4,6,8 and 10) V is investigated based on the same source voltage sequence and smooth load variation considered in the scenario II and III respectively. Fig. 16 depicts the waveform of the converter's output using the optimized PID gain parameters. It is evident from the miniplotes in Fig. 16 that the optimizing PSO-PID control system guided the converter's output signal through the varying reference voltage trajectory efficiently. The optimized controller delivered a quick transient output voltage (20 ms rise time, 24 ms settling time) with low oscillation steady state response. However, an overshoot of $35\%$ was seen at response times in which there were no simultaneous changes in the values of load resistance and reference voltage.

More hard-working circumstance is also adopted in this study to examine the robustness of the presented electronic PID controller strategy.

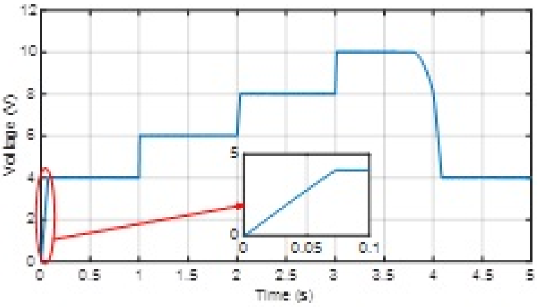

Fig. 16. Converter response based on supply and reference disturbances and smooth load variations

By utilizing the same sharp change in the reference signal, applied voltage, and load resistance that was considered in the previous working scenarios II, III and IV respectively, the output signal of the converter is shown in Fig. 17. It is clearly evident from the miniplots in Fig. 17 that the Buck regulator under the influence of the PID controller is capable of equipping a variable resistive load with a constant DC voltage. The optimized PID controller is also sent to the load a fast transient DC voltage (13 ms rise time, 16 ms settling time) with low fluctuating steady state output voltage. However, there are overshoots with maximum value of 1 V appeared at the resistance change times, which have been reduced significantly with increasing time.

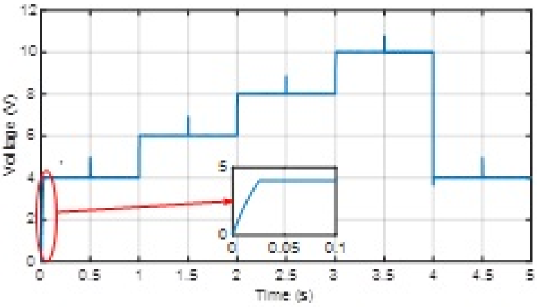

Fig. 17. Converter response based on reference and source voltage disturbances with sharp changing load

## VIII. CONCLUSIONS AND FUTURE WORK

This study proposed a step-down Buck converter system with disturbances used to provide a resistive load by DC voltage. The output voltage of the Buck converter was regulated using an electronic PID controller. The controller circuit is constructed using analog components. The realism of the introduced regulator scheme was enhanced through utilizing the MATLAB/Simscape toolbox, which is employed to build circuits of the Buck regulator and its analog PID feedback controller. The circuit of the system was realized through taking into account practical factors, (tolerance, series resistance, parasitic capacitors) in modeling process of the PID-based converter.

PSO algorithm was adopted to find optimum value for PID proportional, integral and derivation parameters. Based on the optimized values of the gain parameters, the electronic circuit of the PID controller was designed. The Buck regulator circuit and analog PID control system were simulated utilizing MATLAB/Simscape toolbox to validate the proposed power system.

In this work, to certify the robustness of the introduced power scheme, the voltage adjustment action of the Buck regulator under the influence of the analog PID controller was tested at hard uncertain working conditions. The findings of the system simulation demonstrated the activity and robustness of the analog PID controller in rejecting the influence of system uncertainties and providing a fast and stable output response. Based on the hard working scenario, voltage changes and load disturbance, the results obtained from the system showed good response with rise time of 20 ms, settling time of 24 ms, minimal steady state error, zero overshoot voltage through soft change case in the resistive load and transient overshoot voltage of no more than 1 V in times of sharp change in resistive load.

In the prospective work, the presented Buck converter system under voltage turbulence and load uncertainty conditions will be implemented experimentally to confirm the efficiency of the introduced analog PID controller and show the adaptability of the presented converter in the industrial and renewable energy applications.

## REFERENCES

[1] A. K. Gupta, D. Kumar, B. M. Reddy and P. Samuel, "BBBC based optimization of PI controller parameters for buck converter," *2017 Innovations in Power and Advanced Computing Technologies (i-PACT)*, pp. 1-6, 2017, doi: 10.1109/IPACT.2017.8244983.

[2] S. Kaitwanidvilai, P. Olranthichachat and M. Parnichkun, "Fixed structure robust loop shaping controller for a buck-boost converter using genetic algorithm," *Proceedings of the International MultiConference of Engineers and Computer Scientists*, vol. 2, pp. 24–28, 2008.

[3] M. Harfman Todorovic, L. Palma and P. N. Enjeti, "Design of a Wide Input Range DC–DC Converter With a Robust Power Control Scheme Suitable for Fuel Cell Power Conversion," in *IEEE Transactions on Industrial Electronics*, vol. 55, no. 3, pp. 1247-1255, 2008, doi: 10.1109/TIE.2007.911200.

[4] V. Viswanatha and R. Reddy, "Microcontroller based bidirectional buck-boost converter for photo-voltaic power plant," *Journal of Electrical Systems and Information Technology*, vol. 5, no. 3, pp. 745–758, 2018, doi: 10.1016/j.jesit.2017.04.002.

[5] M. Kaouane, A. Boukhelifa and A. Cheriti, "Regulated output voltage double switch Buck-Boost converter for photovoltaic energy application," *2015 3rd International Renewable and Sustainable Energy Conference (IRSEC)*, pp. 1-6, 2015, doi: 10.1109/IRSEC.2015.7455114.

[6] K. Balamurugan, V. Nandalal, G. Suresh, B. M. Shankar and B. Srirevathi, "Comparative Analysis of CUK, SEPIC, Buck-Boost and ZETA Converters to Reduce Commutation Torque Ripple in

BLDC Motor," *2022 International Conference on Advanced Computing Technologies and Applications (ICACTA)*, pp. 1-7, 2022, doi: 10.1109/ICACTA54488.2022.9753362.

[7] Z. Qian, O. Abdel-Rahman, H. Al-Atrash and I. Batarseh, "Modeling and Control of Three-Port DC/DC Converter Interface for Satellite Applications," in *IEEE Transactions on Power Electronics*, vol. 25, no. 3, pp. 637-649, 2010, doi: 10.1109/TPEL.2009.2033926.

[8] C. Zhang, J. Wang, S. Li, B. Wu and C. Qian, "Robust Control for PWM-Based DC–DC Buck Power Converters With Uncertainty Via Sampled-Data Output Feedback," in *IEEE Transactions on Power Electronics*, vol. 30, no. 1, pp. 504-515, 2015, doi: 10.1109/TPEL.2014.2299759.

[9] S. M. Ghamari, F. Khavari and H. Mollaee, "Adaptive back stepping controller design for DC/DC buck converter optimised by grey wolf algorithm," *IET Energy Systems Integrations*, vol. 6, no. 1, pp. 18–30, 2023, doi: 10.1049/esi2.12098.

[10] E. Meyer, Z. Zhang and Y. -F. Liu, "An Optimal Control Method for Buck ConvertersUsing a Practical Capacitor ChargeBalance Technique," in *IEEE Transactions on Power Electronics*, vol. 23, no. 4, pp. 1802-1812, 2008, doi: 10.1109/TPEL.2008.925201.

[11] S. A. Lindiya, K. Vijayarekha and S. Palani, "Deterministic LQR controller for dc-dc Buck converter," *2016 Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTSE)*, pp. 1-6, 2016, doi: 10.1109/PESTSE.2016.7516450.

[12] C. O. Moreira, F. A. Silva, S. F. Pinto and M. B. Santos, "Digital LQR control with Kalman Estimator for DC-DC Buck converter," *2011 IEEE EUROCON - International Conference on Computer as a Tool*, pp. 1-4, 2011, doi: 10.1109/EUROCON.2011.5929326.

[13] Chin Chang, "Robust control of DC-DC converters: the buck converter," *Proceedings of PESC '95 - Power Electronics Specialist Conference*, vol. 2, pp. 1094-1097, 1995, doi: 10.1109/PESC.1995.474951.

[14] M. Mazwin, H. Noor, C. Chanuri, F. Nur, I. Nurul and A. Mohd, "State feedback controller using pole placement method for linear buck converter to improve overshoot and settling time," *Applied Mechanics and Materials*, vol. 793, pp. 211–215, 2015, doi: 10.4028/www.scientific.net/AMM.793.211.

[15] S. K. Mazumder, A. H. Nayfeh and A. Borojevic, "Robust control of parallel DC-DC buck converters by combining integral-variable-structure and multiple-sliding-surface control schemes," in *IEEE Transactions on Power Electronics*, vol. 17, no. 3, pp. 428-437, 2002, doi: 10.1109/TPEL.2002.1004251.

[16] C. H. Rivetta, A. Emadi, G. A. Williamson, R. Jayabalan and B. Fahimi, "Analysis and control of a buck DC-DC converter operating with constant power load in sea and undersea vehicles," in *IEEE Transactions on Industry Applications*, vol. 42, no. 2, pp. 559-572, 2006, doi: 10.1109/TIA.2005.863903.

[17] S. Maity, "Dynamics and Stability Issues of a Discretized Sliding-Mode Controlled DC-DC Buck Converter Governed by Fixed-Event-Time Switching," in *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 60, no. 6, pp. 1657-1669, 2013, doi: 10.1109/TCSI.2012.2221193.

[18] R. Ling, D. Maksimovic and R. Leyva, "Second-Order Sliding-Mode Controlled Synchronous Buck DC–DC Converter," in *IEEE Transactions on Power Electronics*, vol. 31, no. 3, pp. 2539-2549, 2016, doi: 10.1109/TPEL.2015.2431193.

[19] S. -C. Tan, Y. M. Lai and C. K. Tse, "General Design Issues of Sliding-Mode Controllers in DC–DC Converters," in *IEEE Transactions on Industrial Electronics*, vol. 55, no. 3, pp. 1160-1174, 2008, doi: 10.1109/TIE.2007.909058.

[20] J. S. Fang, S. -H. Tsai, J. -J. Yan, P. L. Chen and S. -M. Guo, "Realization of DC–DC Buck Converter Based on Hybrid $H_2$ Model Following Control," in *IEEE Transactions on Industrial Electronics*, vol. 69, no. 2, pp. 1782-1790, 2022, doi: 10.1109/TIE.2021.3062268.

[21] S. Kapat, P. S. Shenoy and P. T. Krein, "Near-Null Response to Large-Signal Transients in an Augmented Buck Converter: A Geometric Approach," in *IEEE Transactions on Power Electronics*, vol. 27, no. 7, pp. 3319-3329, 2012, doi: 10.1109/TPEL.2011.2181418.

[22] S. Saadatmand, P. Shamsi and M. Ferdowsi, "The Voltage Regulation of a Buck Converter Using a Neural Network Predictive Controller," *2020 IEEE Texas Power and Energy Conference (TPEC)*, pp. 1-6, 2020, doi: 10.1109/TPEC48276.2020.9042588.

[23] G. Garcera, E. Figueres and A. Mocholi, "Novel three-controller average current mode control of DC-DC PWM converters with improved robustness and dynamic response," in *IEEE Transactions on Power Electronics*, vol. 15, no. 3, pp. 516-528, 2000, doi: 10.1109/63.844512.

[24] E. Figueres, G. Garcera, J. M. Benavent, M. Pascual and J. A. Martinez, "Adaptive two-loop Voltage-mode control of DC-DC switching converters," in *IEEE Transactions on Industrial Electronics*, vol. 53, no. 1, pp. 239-253, 2006, doi: 10.1109/TIE.2005.862254.

[25] U. Kaithamalai, L. Ponnusamy and B. Kandasamy, "Hybrid posicast controller for a DC-DC Buck converter," *Serbian Journal of Electrical Engineering*, vol. 5, no. 1, pp. 121–138, 2008, doi: 10.2298/SJEE0801121K.

[26] I. K. Mohammed, "Design of Optimized PID Controller Based on ABC Algorithm for Buck Converters with Uncertainties," *Journal of Engineering Science and Technology*, vol. 16, no. 5, pp. 404-4059, 2021, doi: 10.5772/intechopen.94907.

[27] M. N. Ahmed, I. K. Mohammed and A. T. Younis, "Design and Implementation of PSO/ABC Tunned PID Controller for Buck Converters," *Periodicals of Engineering and Natural Sciences (PEN)*, vol. 9, no. 4, pp. 643–656, 2021, doi: 10.21533/pen.v9i4.2411.

[28] I. K. Mohammed, A. I. Abdulla and J. M. Ahmed, "Speed Control of DC Motor Using MRAC and Genetic Algorithm Based PID Controller," *International Journal of Industrial Electronics and Electrical Engineering*, vol. 8, no. 1, pp. 1–6, 2020.

[29] L. A. Khalaf. O. T. Mahmood A. M. T. Ibraheem, "Smart Speed Control of BLDC Motor Using Programmable Logic Controller," *Przeglad Elektrotechniczny,* vol. 2023, no. 1, pp. 48–53, 2023, doi: 10.15199/48.2023.01.09.

[30] S. Kapat and P. T. Krein, "Formulation of PID Control for DC–DC Converters Based on Capacitor Current: A Geometric Context," in *IEEE Transactions on Power Electronics*, vol. 27, no. 3, pp. 1424-1432, 2012, doi: 10.1109/TPEL.2011.2164423.

[31] R. Priewasser, M. Agostinelli, C. Unterrieder, S. Marsili and M. Huemer, "Modeling, Control, and Implementation of DC–DC Converters for Variable Frequency Operation," in *IEEE Transactions on Power Electronics*, vol. 29, no. 1, pp. 287-301, 2014, doi: 10.1109/TPEL.2013.2248751.

[32] E. W. Zurita-Bustamante, J. Linares-Flores, E. Guzman-Ramirez and H. Sira-Ramirez, "A Comparison Between the GPI and PID Controllers for the Stabilization of a DC–DC "Buck" Converter: A Field Programmable Gate Array Implementation," in *IEEE Transactions on Industrial Electronics*, vol. 58, no. 11, pp. 5251-5262, 2011, doi: 10.1109/TIE.2011.2123857.

[33] Y. Lu, *et al*., "Design of PID Controller Based on ELM and Its Implementation for Buck Converters," International Journal of Control, Automation and Systems*International Journal of Control, Automation and Systems*, vol. 19, no. 1, pp. 2479–2490, 2021, doi: 10.1007/s12555-019-0989-1.

[34] L. Guo, J. Y. Hung and R. M. Nelms, "Evaluation of DSP-Based PID and Fuzzy Controllers for DC–DC Converters," in *IEEE Transactions on Industrial Electronics*, vol. 56, no. 6, pp. 2237-2248, 2009, doi: 10.1109/TIE.2009.2016955.

[35] N. J. Dahl, P. L. Muntal and M. A. E. Andersen, "Fully Time-Based PID Controller for a High Frequency Buck Converter," *2023 21st IEEE Interregional NEWCAS Conference (NEWCAS)*, pp. 1-5, 2023, doi: 10.1109/NEWCAS57931.2023.10198133.

[36] A. I. Abdulla and I. K. Mohammed, "Aircraft pitch control design using LQG controller based on genetic algorithm," *Telecommunication Computing Electronics and Control*, vol. 21, no. 2, pp. 401–417, 2023, doi: 10.12928/telkomnika.v21i2.22051.

[37] A. Prodic and D. Maksimovic, "Design of a digital PID regulator based on look-up tables for control of high-frequency DC-DC converters," *2002 IEEE Workshop on Computers in Power Electronics*, pp. 18-22, 2002, doi: 10.1109/CIPE.2002.1196709.

[38] A. Kelly and K. Rinne, "Control of dc-dc converters by direct pole placement and adaptive feedforward gain adjustment," *Twentieth Annual IEEE Applied Power Electronics Conference and Exposition*, vol. 3, pp. 1970-1975, 2005, doi: 10.1109/APEC.2005.1453326.

[39] J. Shalini and N. S. Beniwal, "PID controller for DC-DC converter using Ziegler Nicholas method," *International Journal for Scientific Research and Development*, vol. 3, no. 6, pp. 947–949, 2015.

[40] A. Alnaib, N. Sultan and O. Mahmood, "Design a Fuel cell-based drive DC motor for an electric vehicle application," *International Journal of*

*Engineering & Technology*, vol. 7, no. 4, pp. 2081–2087, 2018, doi: 10.14419/ijet.v7i4.16308.

[41] A. M. Alnaib, O. T. Mahmood and N. S. Sultan, "Design of genetic algorithm controller to fuel cell fed SEIG derived by DC motor," *International Journal of Engineering & Technology*, vol. 7, no. 4, pp. 4141–4145, 2018.

[42] C. H. Cheng, P. J. Cheng and M. J. Xie, "Current sharing of paralleled DC-DC converters using GA-based PID controllers," *Expert Systems with Applications*, vol. 37, no. 1, pp. 733–740, 2010, doi: 10.1016/j.eswa.2009.05.083.

[43] O. T. Altinoz and H. Erdem, "Evaluation function comparison of particle swarm optimization for buck converter," *SPEEDAM 2010*, pp. 798-802, 2010, doi: 10.1109/SPEEDAM.2010.5542160.

[44] O. T. Altinoz and H. Erdem, "Particle swarm optimisation-based PID controller tuning for static power converters," *International Journal of Power Electronics*, vol. 7, no. 1, pp. 16–35, 2015, doi: 10.1504/IJPELEC.2015.071197.

[45] A. Jalilvand, H. Vahedi and A. Bayat, "Optimal tuning of the PID controller for a buck converter using Bacterial Foraging Algorithm," *2010 International Conference on Intelligent and Advanced Systems*, pp. 1-5, 2010, doi: 10.1109/ICIAS.2010.5716105.

[46] D. M. M. S. Regis, S. P. Kumar and G. G. Devadhas, "An optimum setting of controller for a dc-dc converter using bacterial intelligence technique," *ISGT2011-India*, pp. 204-210, 2011, doi: 10.1109/ISET-India.2011.6145383.

[47] E. Isen, "Determination of Different Types of Controller Parameters Using Metaheuristic Optimization Algorithms for Buck Converter Systems," in *IEEE Access*, vol. 10, pp. 127984-127995, 2022, doi: 10.1109/ACCESS.2022.3227347.

[48] R. Liu, T. Wang, J. Zhou, X. Hao, Y. Xu and J. Qiu, "Improved African Vulture Optimization Algorithm Based on Quasi-Oppositional Differential Evolution Operator," in *IEEE Access*, vol. 10, pp. 95197-95218, 2022, doi: 10.1109/ACCESS.2022.3203813.

[49] S. -Y. Chen, B. -C. Yang, T. -A. Pu, C. -H. Chang and R. -C. Lin, "Active Current Sharing of a Parallel DC-DC Converters System Using Bat Algorithm Optimized Two-DOF PID Control," in *IEEE Access*, vol. 7, pp. 84757-84769, 2019, doi: 10.1109/ACCESS.2019.2925064.

[50] S. I. Saadi and I. K. Mohammed, "Power Control Approach for PV Panel System Based on PSO and INC Optimization Algorithms," *Journal Europeen des Systemes Automatises*, vol. 55, no. 6, pp. 825–843, 2022, doi: 10.18280/jesa.550615.

[51] I. K. Mohammed and M. N. Noman, "Optimal Control Approach for Robot System Using LQG Technique," *Journal Europeen des Systemes Automatises*, vol. 55, no. 5, pp. 671–677, 2022, doi: 10.18280/jesa.550513.

[52] A. Debnath, T. O. Olowu, S. Roy, I. Parvez and A. Sarwat, "Particle Swarm Optimization-based PID Controller Design for DC-DC Buck Converter," *2021 North American Power Symposium (NAPS)*, pp. 1-6, 2021, doi: 10.1109/NAPS52732.2021.9654737.

[53] M. Adeel, U. Fayyaz, U. Rafi and M. Umar Farooq, "Design of a Buck Converter with an Analogue PI Controller for Wide Load Range Applications," *2023 4th International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)*, pp. 1-5, 2023, doi: 10.1109/iCoMET57998.2023.10099295.

[54] I. K. Mohammed, "Design and Simulation of Voltage Control System for Simscape Boost Converter Model With Disturbances," *International Journal of Control, Automation and Systems*, vol. 22, no. 5, pp. 1707–1716, 2024, doi: 10.1007/s12555-023-0311-0.

[55] A. Elasser and D. A. Torrey, "Soft switching active snubbers for DC/DC converters," *Proceedings of 1995 IEEE Applied Power Electronics Conference and Exposition - APEC'95*, vol. 1, pp. 483-489, 1995, doi: 10.1109/APEC.1995.468991.

[56] B. A. Altuğ, A. Kababiyik, E. Dincol and C. Batunlu, "Buck Converter with Optocoupler Based Switching," *2021 8th International Conference on Electrical and Electronics Engineering (ICEEE)*, pp. 184-190, 2021, doi: 10.1109/ICEEE52452.2021.9415957.

[57] J. A. Solsona, S. G. Jorge and C. A. Busada, "Nonlinear Control of a Buck Converter Which Feeds a Constant Power Load," in *IEEE Transactions on Power Electronics*, vol. 30, no. 12, pp. 7193-7201, 2015, doi: 10.1109/TPEL.2015.2392371.

[58] M. Gheisarnejad, H. Farsizadeh and M. H. Khooban, "A Novel Nonlinear Deep Reinforcement Learning Controller for DC–DC Power Buck Converters," in *IEEE Transactions on Industrial Electronics*, vol. 68, no. 8, pp. 6849-6858, 2021, doi: 10.1109/TIE.2020.3005071.

[59] N. Swaminathan, L. N and Y. Cao, "DCM and CCM Operation of Buck-Boost Full-Bridge DC-DC Converter," *2021 IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 292-297, 2021, doi: 10.1109/APEC42165.2021.9487340.

[60] M. -L. Chiu, I. -F. Lo and T. -H. Lin, "A Time-Domain CCM/DCM Current-Mode Buck Converter with a PI Compensator Incorporating an Infinite Phase Shift Delay Line," *ESSCIRC 2023- IEEE 49th European Solid State Circuits Conference (ESSCIRC)*, pp. 441-444, 2023, doi: 10.1109/ESSCIRC59616.2023.10268745.

[61] P. Azer and A. Emadi, "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, 2020, doi: 10.1109/ACCESS.2020.2987277.

[62] M. H. Rashid, *Power Electronics Handbook: Devices, Circuits and Applications*, Butterworth-heinemann, 2007.