Data-Driven PID Control for DC/DC Buck-Boost Converter-Inverter-DC Motor based on Safe Experimentation Dynamics

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Abstract— **This research paper presents a data-driven PID control for a DC/DC Buck-Boost converter-inverter-DC motor system based on safe experimentation dynamics (SED). The data-driven is a control scheme refers to a controller that is designed using the input-output data measurement obtained from an actual plant. Then, the data-driven scheme required an optimization tool for finding the optimal parameter controller design with the help of the running data. Hence, the SED is an optimization method provides high accuracy solution by keeping the best controller parameter values based on the input-output data measurement. Moreover, the SED method is a single agent-based optimization that provides a fast solution in order to find an optimal solution, especially in the high dimensional problem. Apart from that, a proportional-integral-derivative (PID) controller structure is chosen due to its simple structure and robust performance that allows it to be used for a wide range of operating conditions. The performance of the data-driven PID control based on the SED method is evaluated by an extensive numerical example based on the tracking performance and computational time for DC/DC buck-boost inverter-converter of DC motor. In addition, the performance accuracy of the SED based method is compared to simultaneous perturbation stochastic approximation (SPSA) based method. The simulation results show that the data-driven PID based on the SED is capable to track the trajectory task given and obtain a better control accuracy as compared to the SPSA based method.**

Index terms: – PID; tracking trajectory; data-driven; buck-boost converter; bidirectional.

I. INTRODUCTION

Up to now, the power electronic converters are widely used in various industrial application such as renewable energies, aircraft, electric vehicles, robots, and telecommunications [1]–[3]. In certain applications, power electronics converter is involved with high precision of movement with elaborated the power electronics converter circuit and motors connection in both commanded with the control strategy. In order to control the angular velocity of the unidirectional motor, most of the researchers focus on power electronics converter in buck or boost configurations depends on the applications [4], [5]. On the other hands, to control the angular velocity of the bidirectional motor, the buck-boost converter-inverter configuration has been proposed by [6], [7].

So far, many control strategies have been reported in order to control the trajectory tracking in power electronics converter powered DC motors such as proportional-Integral (PI), fuzzy-logic-control (FLC-PI), linear quadratic regulator (LQR), sigmoid-PI and etc [4], [5], [8], [9]. However, most of this control strategies proposed only for unidirectional angular velocity that controls the buck or boost converter separately while less reported on bidirectional angular velocity problem. At present, the passivity-based control method has been proposed to control the angular velocity of the bidirectional motor [7], [10]. This passivity-based control design method is a model-based approach utilized the Lyapunov and Sylvester criterion. But, this model-based control method is fully depending on plant modelling that may contribute several drawbacks, such as inaccuracy of the simplified model obtained and bring the huge gap between control theory and real applications. This problem will contribute less control performance of the system.

Thus, the data-driven control scheme is a convincing method to provide a better solution to the problem. This is due to the data-driven is designed based on the information from the input and output data measurement [11], [12]. The concept of the data-driven scheme is to determine the controller parameters by running an actual plant repeatedly according to a specific time until the best control objective is achieved. In addition, the control objective is assessed in terms of increasing the control accuracy of the system by minimizing the total measurement error and input of the controlled system [13]. Therefore, it is clear that data-driven provides the best tuning strategy due to its capability in adapting to the changes in the plant structure during the tuning process. Here, the PID controller was selected as pre-specific fixed controller structure in data-driven scheme due to its widely used in industry, robustness, less complexity in the design and easy to implement [14][15].

In order to tune the PID parameters, the single agent optimization method such as simultaneous perturbation stochastic approximation (SPSA) is widely used in the data-driven scheme [16], [17]. Specifically, the SPSA refers to the approximate gradient that is based on only a small number of measurements of the objective function. In addition, SPSA required two measurements of the objective function are required per iteration in order to update the design parameter. However, it was discovered that the SPSA unable to find the optimal value due to the memoryless specification and could involve with a high possibility to produce unstable convergence [18]. Apart from that, the updated law of the SPSA is dependent on the gain sequence [16]. For example, the step size that depending on gain sequence will decrease if the number of iteration increases. Therefore, it can be clearly understood that the SPSA does not have sufficient energy to re-adjust the step size in order to find the new optimal solution, particularly when disturbances, uncertainties, and delay occur during the tuning process.

Therefore, the SED method would be a solution and provide better performance in finding optimal parameter. This due to its capability to keep the best parameter value and produce stable convergence even in an unfeasible region [12], [14]. In addition, the SED method also has a fixed interval size that independent to the number of iterations that affects the gain sequence. Therefore, this will allow the SED method to have adequate energy to re-adjust in the attempted of finding the new optimal solution. Thus, the SED method would be beneficial to observe the performance in tuning the PID parameters for power electronics DC/DC buck-boost converter-inverter-DC motor system.

This paper aims to investigate the data-driven PID control based on the SED based method to control the trajectory tracking for buck-boost converter voltage and bidirectional-angular velocity of DC motor. The contributions of this work include the following:

i) To verify the SED based method provides better control performance of accuracy compared to SPSA based method since it can memorize the best parameter value and their coefficients did not depend on iteration like the SPSA method.

ii) To demonstrate the SED based method is fast computational time compare to SPSA due to only one objective function evaluation per iteration while SPSA required two measurements of the objective function per iteration.

The structure of this paper as follows. In Section 2, the problem setting of PID controller structure design in minimizing the error of the DC/DC buck-boost converter-inverter-DC motor. Section 3, represent the SED algorithm while section 4 shows the design of data-driven PID control. In section 5, the implementation of the SED approach, which is used to find the parameter of PID is summarized. Section 6 presents the control performances of results with the discussion. Then, in section 7, a conclusion of findings is presented.

II. PROBLEM SETTING

Fig. 1 illustrates the control system of the DC/DC buck-boost converter-inverter-DC motor with PID control structure. The system is represented by G and the symbols of $\boldsymbol{r}(t)\in\mathbb{R}^2$, $\boldsymbol{u}(t)\in\mathbb{R}^2$ and $\boldsymbol{y}(t)\in\mathbb{R}^2$ are referred to the reference, the input control, and the output system, respectively. Consider the input plant, $\boldsymbol{u}(t)=\left[u_{1av}(t)\quad u_{2av}(t)\right]^T\in\mathbb{R}^2$, the converter voltage $y_1(t)=v(t)$ and bidirectional angular velocity $y_2(t)=\omega(t)$.

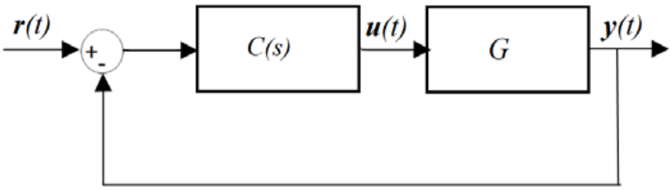


Figure 1: Overall the closed-loop control system

The PID controller $C(s)$ is defined as

$$C(s)=\begin{bmatrix} h_{11}(s) & 0 \\ 0 & h_{22}(s) \end{bmatrix} \tag{1}$$

where

$$h_{11}(s)=K_{P11}\left(1+\frac{1}{-K_{I11}s}+\frac{K_{D11}s}{1+\left(K_{D11}/N_{11}\right)s}\right) \tag{2}$$

and

$$h_{22}(s)=-K_{P22}\left(1+\frac{1}{K_{I22}s}+\frac{K_{D22}s}{1+\left(K_{D22}/N_{22}\right)s}\right). \tag{3}$$

The variables $K_{P11},K_{P22}\in\mathbb{R}$, $K_{I11},K_{I22}\in\mathbb{R}$, $K_{D11},K_{D22}\in\mathbb{R}$ and $N_{11},N_{22}\in\mathbb{R}$ are refers to proportional gain, integral gain, derivative gain and filter coefficient, respectively.

Thus, the corresponding performance index according to the control system in Fig. 1 is

$$J\left(\boldsymbol{K_P},\boldsymbol{K_I},\boldsymbol{K_D},\mathbf{N}\right)=\sum_{j=1}^{2}w_{1j}\int_{t_0}^{t_f}\left|r_j(t)-y_j(t)\right|^2dt, \tag{4}$$

where $r_j(t)$ and $y_j(t)$ are the *j*-th output elements and *i*-th is input elements of the vectors $\boldsymbol{r}(t)$ and $\boldsymbol{y}(t)$ respectively. Then the $t_0\in\{0\}\cup\mathbb{R}_+$ and $t_f\in\mathbb{R}_+$ where the $[t_0,t_f]$ is time interval refers to the performance evaluation period. The PID parameters $\boldsymbol{K_P}:=[K_{P11}\quad K_{P22}]^{\mathrm{T}}$, $\boldsymbol{K_I}:=[K_{I11}\quad K_{I22}]^{\mathrm{T}}$, $\boldsymbol{K_D}:=[K_{D11}\quad K_{D22}]^{\mathrm{T}}$, $\mathbf{N}:=[N_{11}\quad N_{22}]^{\mathrm{T}}$, and $w_{1i}\in\mathbb{R}$ $(i=1,2)$ is the weighting coefficients.

Problem 2.1. Find PID controller parameters $C(s)$ in Fig. 1, which minimizes the objective function $J\left(\boldsymbol{K_P},\boldsymbol{K_I},\boldsymbol{K_D},\mathbf{N}\right)$ with respect to parameters $\boldsymbol{K_P},\boldsymbol{K_I},\boldsymbol{K_D}$ and $\mathbf{N}$ based on $\boldsymbol{u}(t)$ and $\boldsymbol{y}(t)$.

III. DATA-DRIVEN PID TUNING

In this part, the details properties of solution for Problem 2.1 are described. First, the details of safe experimentation dynamics (SED) algorithm is presented [19]. Second, the execution of the data-driven PID control design method for minimizing the error trajectory tracking of converter voltage and bidirectional angular velocity of the DC motor is described.

A. Safe Experimentation Dynamics

Consider

$$\min_{\boldsymbol{p}\in\mathbb{R}^n} f\left(\boldsymbol{p}\right), \tag{5}$$

as an optimization problem that minimizes the objective function $f\left(\boldsymbol{p}\right)$ by selection of the design parameter $\boldsymbol{p}\in\mathbb{R}^n$. The optimal solution of the design parameter corresponds to the optimization problem. The optimal solution is obtained by continually updating the design parameter using the SED based method. The SED updated law is

$$p_i(k+1) = h(\overline{p}_i - K_g rv_2), \tag{6}$$

where the number of iterations is $k = 0,1,...k_{\max}$. The design parameter $p_i \in \mathbb{R}$ is the i^{th} element of $\boldsymbol{p}\in\mathbb{R}^n$, $\overline{p}_i \in \mathbb{R}$ is the i^{th} element of $\overline{\boldsymbol{p}}\in\mathbb{R}^n$. Notes that, $\overline{\boldsymbol{p}}$ is used to keep the present best value of the design parameters. The K_g is interval size to decide on random steps on the design parameter $p_i \in \mathbb{R}$. Then, $rv_2 \in \mathbb{R}$ is a random number generated by a computer. Next, the function h in Equation (6) is defined as

$$h\left(\bullet\right) = \begin{cases} p_{\max}, & \chi > p_{\max}, \\ \chi, & p_{\min} < \chi < p_{\max}, \\ p_{\min}, & \chi < p_{\min}, \end{cases} \tag{7}$$

where the new value of the design parameter $\chi = \overline{p}_i - K_g rv_2$. The $p_{\max}$ and $p_{\min}$ are the pre-defined maximum and minimum values of the design parameters, respectively. The steps of the SED method follow as in Fig. 2.

Notes that, the E is the probability in scalar value used to set new random value for design parameter $\boldsymbol{p}$. The $\overline{f}$ is uses to keep the current best value of the objective function. Next, $rv_1 \in \mathbb{R}$ is the value of random number which is chosen by uniformly distribute between 0 and 1, while rv_2 is between $p_{\min}$ and $p_{\max}$.

B. Data-driven PID control design

For this section, the PID controller design is presented, where the design parameter is stated as

$$\boldsymbol{LS} = \left[\boldsymbol{K_P}, \boldsymbol{K_I}, \boldsymbol{K_D}, \boldsymbol{N}\right]^T \in \mathbb{R}^8. \tag{8}$$

The logarithmic scale is employed to parameters $\boldsymbol{p}$ to accelerate the exploration of the design parameter to obtain a fast design parameter searching, a logarithmic scale is employed to each element of $\boldsymbol{LS}$ by setting $LS_i = 10^{p_i}\ (i = 1,2,.....8)$ and the objective function is expressed as $J = \left[10^{p_1} \quad 10^{p_2} \quad ... \quad 10^{p_8}\right]^T$. Fig. 3 shows the PID controller parameters tuning procedures in finding an optimal solution for the system.

Remarks 3.1: Note that, during the optimization process, there is a high possibility that the updated PID parameters contribute to the right-hand side of closed-loop poles and trapped in an unfeasible region. In order to solve this problem, norm-limited SPSA has been proposed by [18]. There, a saturation function δ was introduced to avoid the large value of the design parameter generated by the SPSA based method that will contribute to stable convergence. Hence, in the following part of this work, the norm-limited SPSA based method will be used as SPSA based method.

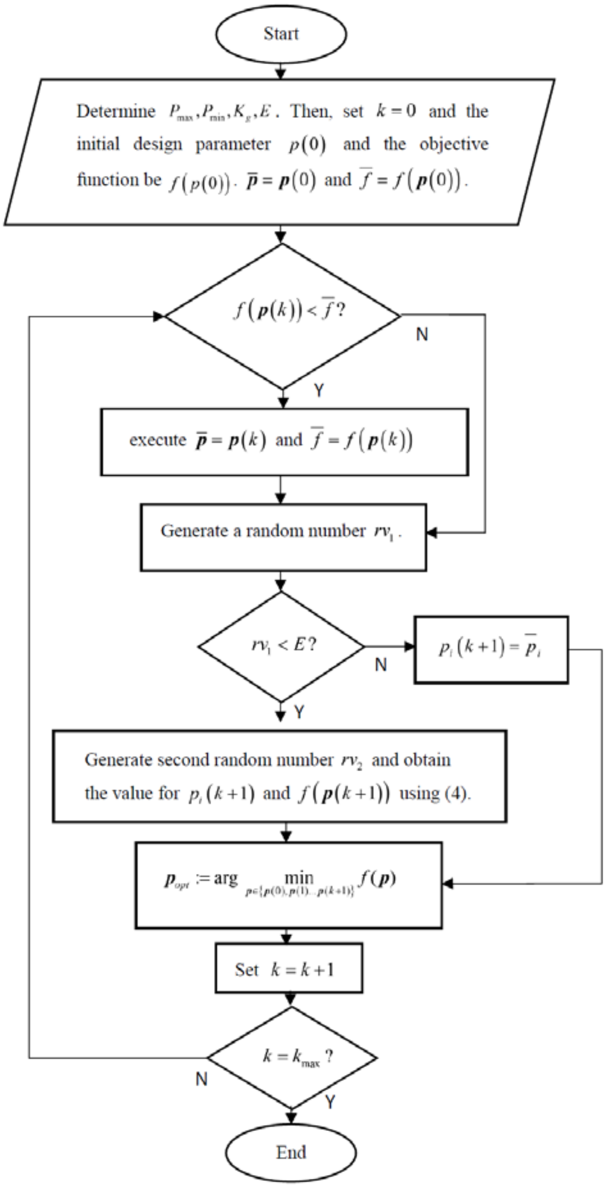
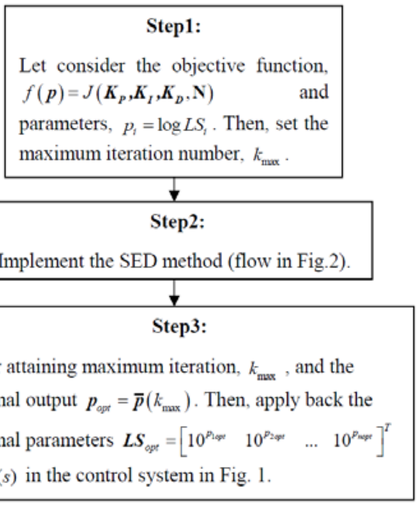


Figure 2: Flow chart of SED algorithm



Step1:

Let consider the objective function, $f(\boldsymbol{p}) = J(\boldsymbol{K_P}, \boldsymbol{K_I}, \boldsymbol{K_D}, \mathrm{N})$ and parameters, $p_i = \log LS_i$. Then, set the maximum iteration number, $k_{\max}$.

Step2:

Implement the SED method (flow in Fig.2).

Step3:

After attaining maximum iteration, $k_{\max}$, and the optimal output $\boldsymbol{p}_{opt} = \bar{\boldsymbol{p}}(k_{\max})$. Then, apply back the optimal parameters $\boldsymbol{LS}_{opt} = \begin{bmatrix} 10^{p_{1opt}} & 10^{p_{2opt}} & \dots & 10^{p_{nopt}} \end{bmatrix}^T$ to $C(s)$ in the control system in Fig. 1.

Figure 3: Data-driven control procedure

IV. RESULT OF SIMULATION

A. Model of DC/DC Buck-Boost Converter-Inverter-DC Motor System

Fig. 4 shows the electronic circuit of the system which is composed of the following stages [7]. The first stage is the DC/DC Buck-Boost converter function to decreases and increases the voltage at the inverter input circuit. The basic converter circuit consists of the power supply E, the transistor Q_1, Capacitor C, load R, inductance L and diode, D. The second stage is an inverter used as switching to control the direction of the current flow entering the DC motor. The inverter consists of four transistors, which as two transistors denoted Q_2 and other two transistors represent $\bar{Q}_2$. If Q_2 is activated, then $\bar{Q}_2$ is deactivated and vice versa. Finally, the last stage is DC motor consists of armature resistant R_a and armature current I_a.

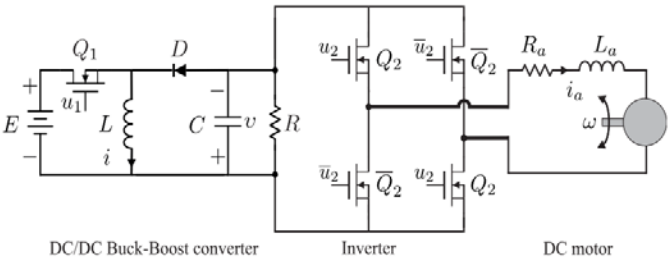


Figure 4: DC/DC Buck-Boost converter–inverter-DC motor system

The model of the DC/DC Buck-Boost converter–inverter-DC motor system, is derived from the Kirchhoff Laws and the mathematical model as follows by [6], [20]

$$C\frac{dv}{dt} = -(1-u_{1av})i - \frac{v}{R} - i_a u_{2av}, \tag{9}$$

$$J\frac{d\omega}{dt} = k_m i_a - b\omega, \tag{10}$$

$$L\frac{di}{dt} = Eu_{1av} + (1-u_{1av})v, \tag{11}$$

$$L_a\frac{di_a}{dt} = vu_{2av} - R_a i_a - k_e\omega, \tag{12}$$

where the inputs average voltage system is bound to $u_{1av} \in [0,1]$ and $u_{2av} \in [-1,1]$. Therefore, the system G in Fig. 1 is represented in Equation (9-12).

B. Numerical Example

The parameters for the DC/DC buck-boost converter-inverter-DC motor system in Fig. 2 are shown in Table I [7]. The sampling time is denoted as $t_s = 0.001$ s. Note that, the current flow through the inductor, i and armature current, i_a is not controlled due to this currents is an idealization of the mathematical model occurred.

TABLE I. PLANT PARAMETERS

Parameter	Value	Parameter	Value
R	$64\ \Omega$,	L	$4.94\,\mathrm{mH}$
C	$114.4\,\mu\mathrm{F}$	R_a	$0.965\,\Omega$
E	$24\,\mathrm{V}$	k_m	120×10^{-3} N.m/A
L_a	$2.22\,\mathrm{mH}$	k_e	120×10^{-3} N.m/A
J	118.2×10^{-3} kg.m^2	b	129.6×10^{-3} N.m.s/rad

The references of tracking trajectory $r_1(t)$ and $r_2(t)$ as follows

$$r_1(t) = -3\Big(\tanh\big(2(t-5)\big)+9\Big), \tag{13}$$

$$r_2(t) = 5\Big(\tanh\big(1(t-5)\big)\Big). \tag{14}$$

The SED coefficients are denoted as $p_{\max} = 5.0$, $p_{\min} = -5.0$, $E = 0.66$ and $K_g = 0.03$. The weights of tracking performance are $w_{11} = 5$, $w_{12} = 5$ and total simulation time is $t_f = 10$ s.

The convergence curve of the objective function based on the SED based method for $k_{\max} = 1000$ iterations in $\boldsymbol{p} \in \mathbb{R}^8$ PID control parameters is illustrated in Fig. 5. The results indicate that the SED based method is able to minimize the objective function and produces a stable convergence. Note that, the SPSA based method applied two objective function evaluations per iteration while the SED based method only requires one objective function evaluation per iteration. Therefore, the maximum iteration of SPSA based method is 500 iterations which is half of the maximum iteration of the SED based method for fair comparative assessment during this simulation.

Next, the initial value for the PID control parameters, $\boldsymbol{p}(0)$ and the optimal PID control parameters, $\boldsymbol{p}_{opt}$ for both SED and SPSA based methods are stated in Table II. The coeficients for SPSA is set to $a(k) = \dfrac{0.03}{(k+100)^{0.8}}$, $c(k) = \dfrac{0.4}{(k+1)^{0.15}}$ and $\delta = 0.02$. Furthermore, statistical results analysis is obtained after 30 trials for each of the algorithms in terms of the objective function, the total norm of error and the computational time are depicted in Table III.

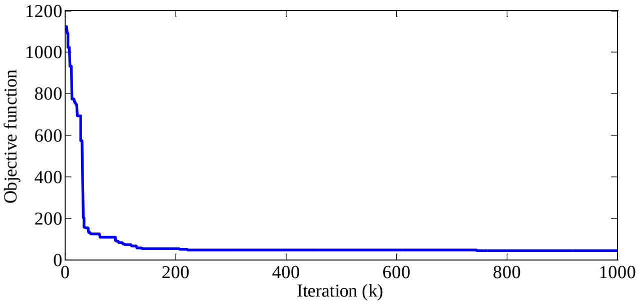


Figure 5: The objective function of the SED based method

This finding shows that the SED based method produces a better control accuracy by obtaining a smaller value of the mean, the best, the worst, the standard deviation of objective function compared to the SPSA based method. The result also indicates that the computational time of the SED based method is lower than the SPSA based method although the total number of iteration is 1000 iterations compared to the SPSA based only 500 iterations. Thus, it is proved that the data-driven PID control based on the SED for DC/DC buck-boost converter-inverter-DC motor system provides a better control performance and computational time of the compared to the SPSA based method.

TABLE II: PARAMETER DESIGN OF PID

$\boldsymbol{LS}$	PID gain	$\boldsymbol{p}(0)$	$\boldsymbol{LS}$	$\boldsymbol{p}_{opt}$		$\boldsymbol{LS}$ corresponded to $\boldsymbol{p}_{opt}$	
				SPSA	SED	SPSA	SED
LS_1	K_{P11}	-3.2	0.0006	-3.1839	-3.8523	0.0007	0.0001
LS_2	K_{I11}	-2	0.0100	-3.2138	-3.6929	0.0006	0.0002
LS_3	K_{D11}	-0.3	0.5012	-0.8847	-0.1641	0.1304	0.6853
LS_4	N_{11}	-0.2	0.6310	-0.8249	-1.3276	0.1497	0.0470
LS_5	K_{P22}	-1.7	0.0200	-1.1929	-0.6269	0.0641	0.2361
LS_6	K_{I22}	0.6	3.9811	-0.8495	-0.3216	0.1414	0.4769
LS_7	K_{D22}	0	1.0000	-0.7739	-0.0549	0.1683	0.8813
LS_8	N_{22}	0.2	1.5849	-0.7177	-0.6617	0.1916	0.2179

TABLE III. STATISTICAL RESULT

Algorithm		SPSA	SED
Objective function $J\left(\boldsymbol{K_P},\boldsymbol{K_I},\boldsymbol{K_D},\mathbf{N}\right)$	Mean	100.6464	**63.7228**
	Best	64.9597	**44.4678**
	Worst	169.9188	**121.314**
	Std.	33.7514	**30.879**
Total norm error $\int_0^{10}\lvert r_1(t)-y_1(t)\rvert^2\,dt\ +$ $\int_0^{10}\lvert r_2(t)-y_2(t)\rvert^2\,dt$	Mean	20.1294	**12.7899**
	Best	12.992	**8.9138**
	Worst	33.9842	**24.263**
	Std.	6.7504	**6.1486**
Comp. time × 10^3		1.0052	**0.658**

The above facts are also supported by the responses of converter voltage and bidirectional angular velocity of DC motor that illustrated in Figs. 6 and 7. The dot green line from both figures represents the reference of trajectory. Then, the thick red line represents the outputs tuning by SPSA based method and the thick blue line represents the output tuning by the SED based method. Then, the thick turquoise line represents the initial parameter response before tuning. Based on the result, it clearly see that the SED based method able to track the desired reference, produce almost zero steady-state error and small overshoot of DC motor angular velocity compared to SPSA based method.

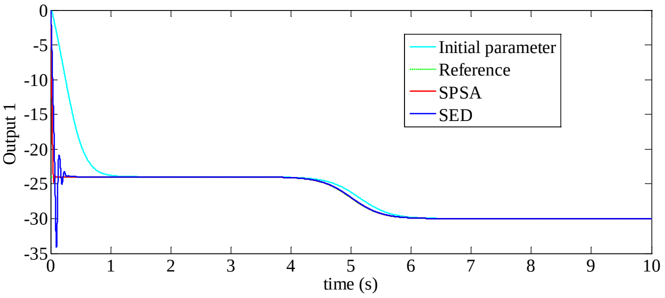


Figure 6: DC/DC buck-boost converter voltage response

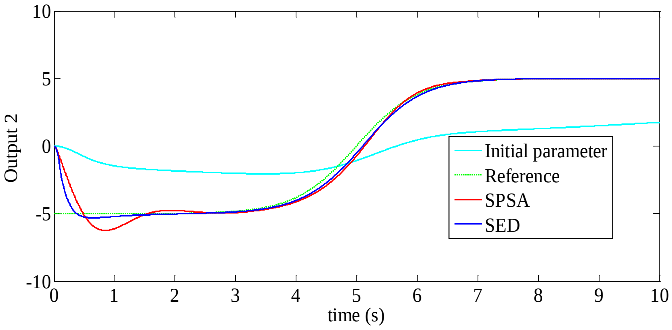


Figure 7: Bidirectional angular velocity of DC motor response

V. CONCLUSION

The performance data-driven PID control based on the SED for DC/DC buck-boost converter-inverter-DC motor system has been presented and investigated. The results of numerical examples show that the SED based method outperform the SPSA based method in terms of lower values of mean, best, worst and standard deviation of the objective function and lower computational time. Hence, it verifies that the memory-based optimization of SED algorithm provides better performance compared to the SPSA algorithm.

ACKNOWLEDGEMENT

This research work was supported by the Fundamental Research Grant Scheme (FRGS) (RDU 160146) by Ministry of Higher Education (MOHE), Government of Malaysia and Universiti Malaysia Pahang.

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