Case-Study:Performance Comparison of Classical and Intelligent Proportional Integral Controller

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***Abstract*—This paper deals with the performance comparison of an Intelligent Proportional Integral Controller and a Classical Proportional Integral Controller for a Pulse Width Modulation (PWM) based DC-DC buck converter operating in Continuous Conduction Mode at a switching frequency of 100KHz. The Intelligent PI controller needs no physical model of the plant to control it, which makes it a suitable choice for controlling the buck converter. The performance of this controller was compared with a classical PI controller to see the superiority of the intelligent controller. The computer simulation proves the superiority through various time domain properties like settling time, rise time, peak time, maximum peak overshoot, steady state ripple voltage etc. The simulation also shows the robustness of the intelligent controller by its automatic adjustment of the performance to varying reference voltages.**

Keywords—Buck Converter, PWM, PI Controller, IntelligentPI Controller.

I. INTRODUCTION

The control of switching mode power converters gains much attention in the research community during the last couple of years due to various reasons. Their application is very widespread. They can be found almost everywhere which includes switching power supply for Desktop, Laptop, Computers, Electric Vehicle, Telecommunication equipment's, home appliances, solar water pump [1] etc. This widespread use necessitates the development of an efficient robust control algorithm that can work within a large operating condition.

A lot of researches have already been done in this domain. One of the widely used techniques to control switching mode power converters is to use Pulse Width Modulation (PWM) [2]. In this method the duty cycle of the switching signal is varied to achieve the desired output response. Again, the input to this PWM block comes from a controller. Popular Controllers are generally from PID family of controllers which include various combination of controllers like P, I, PI, PD etc. PID family of controllers are being used to control switching mode power converters since long ago [3],[4],[5]. In this method, generally averaging and linearization techniques are used to obtain a simple model for the controller design [6],[7],[8]. However, they have a very limited operating condition [9],[10]. They do not offer large signal transient [11]. They failed to perform according to requirements in varying operating condition and under constrained operation. Moreover, they are highly sensitive to parametric uncertainties [12]. All these problems give raise the need of an advanced control algorithm. Figure 1 shows the traditional PI controlled buck converter.

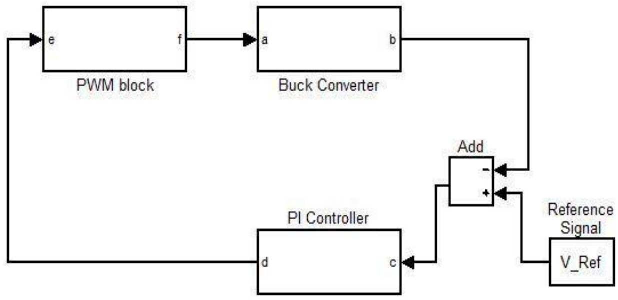

Figure 1. PI controlled buck converter

Different types of modified PID family of controllers were used to reduce the above mentioned problems. This includes-adaptive PID, fuzzy PID [13],[14], Optimization based PID [10] etc. However, the main problem is that all of these techniques need a precise or at least a nominal plant model. In real life, it is not always so easy to obtain a precise mathematical model of the plant under consideration. Sometimes, they are so complex that it is almost impossible. In other cases, partial model can be obtained not full model. Moreover, wear and tear also affects the validity of the model after few months of operation of the plant. As a result, the controller performance degrades because the controller was designed using the original plant model which is no longer valid. Another problem comes from the Linearization. Linearization of the plant model generally done around some operating points. In practice, those operating points can be changed. All these factors lead to the poor performance of the controller. This give rise the need of a control technique which has no or negligible dependence on the plant model. Recently, a control technique of this type was proposed in [15],[16],[17],[18]. This technique is known as Intelligent-PI(I-PI) control. Some application of this technique can be found in [19],[20],[21].

This paper deals with the application of this technique to a switching mode DC-DC buck converter and then compare the performance with classical PI controller. It will be shown that this method has no dependence on the plant model and it can successfully adapt itself to various operating condition while maintaining robust performance in contrast to its classical competitor which has a lot of drawbacks. The paper is organized as follows: Section II contains the detail overview of intelligent PI control technique. Detailed description of Classical PI control strategy can be found in Section III. Section IV will give the mathematical representation of the buck converter operating in continuous conduction mode.Section V deals with the simulation result while the last section i.e. Section VI is devoted for the conclusion.

II. INTELLIGENT PROPORTIONAL INTEGRAL CONTROLLER

The intelligent PI controller is nothing but a modified PI control based on local modeling of the system obtained from the input-output relationship. This is also referred as "Model-Free Control". Details of this relatively new technique can be found in [15], [16], [17], [18]. The overall overview of this technique extracted from the references is summarized below: Let us consider a SISO, finite-dimensional, highly time-varying nonlinear system. Then the input –output behavior of this system around its operating point can be written as following [15]:

$$E\big(t, y, \dot{y}, \ddot{y}, \ldots\ldots, y(a), u, \dot{u}, \ddot{u}, \ldots\ldots, y(b)\big) = 0 \quad (1)$$

Where, u is the input variable and y is the output variable. An assumption is also made for E that it is a sufficiently smoothfunction of its arguments under the condition$\frac{\partial E}{\partial y} \neq 0$.

The input-output equation can be replaced by another model which is referred to as "Phenomenological-model" of very short-time interval validity as:

$$y(v) = F + \alpha u \quad (2)$$

F is the continuously updated local model of the system. So, F can be found at any time instant using numerical differentiation as follows

$$F = y^{(v)} - \alpha u \quad (3)$$

The intelligence of the controller actually lies here in equation (3). In traditional controller synthesis, we consider a fixed model or an uncertain model (around a nominal model) of the system. However, in case of drastic change in the model, the controller cannot perform necessary action. In this intelligent technique, the model is always approximated from the input-output equation which makes this technique immune to change of model.

Considering $v = 1$, the intelligent controller can be written as:

$$u = -\frac{F}{\alpha} + \frac{y^*}{\alpha} + u_c \quad (4)$$

Where, y* is the reference output and component of t actuating signal is u_c .Now, if we choose a classical PI controllerasu_c, we can write this technique as Intelligent PI. The resulting equation is:

$$u = -\frac{F}{\alpha} + \frac{y*}{\alpha} + K_p e + K_i \int e, \quad (5)$$

III. PROPORTIONAL INTEGRAL CONTROLLER

A Proportional Integral (PI) controller is one of the most popular and widely used control techniques in the industry. The PI controller performs the control action based on the error signal. The Error Signal is nothing but the difference between the measured value and the desired set points. The role of the controller is to minimize the error and ultimately taking this error as close as possible to zero.

The basic block diagram of a PI controller is shown in Figure 2. Two constant values are associated with the PI controller named as: the proportional (P) and the integral (I) values. P can be interpreted as a value that depends on the present error while I can be interpreted as an accumulation of the past errors. In order to adjust the process, a weighted sum of these two actions is used.

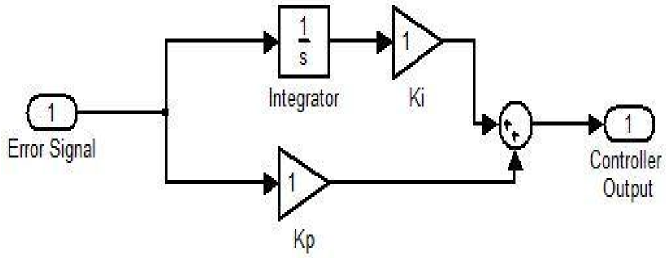

Figure 2. Basic Block Diagram of a PI controller.

The mathematical representation of the control action can be written as:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\, d\tau \quad (6)$$

Where,K_p is the proportional gain,K_i is the integral gain and$e(t)$is the error signal.Proportional gain plays an important role in changing the output response. If$K_p$is very low, then the output response is also very low corresponding to the error signal. The integral action is the sum of the accumulated error. It helps to reduce the steady state error and accelerating the process to set-points. The effect ofK_p and K_i term in system performance is summarized in Table 1[22], [23].

TABLE I. EFFECT OF PROPORTIONAL AND INTEGRAL GAIN ON SYSTEM

CL Performance	**Rise Time**	**Overshoot**	**Settling Time**	**Steady State Error**
K_p	Decrease	Increase	Small Change	Decrease
K_i	Decrease	Increase	Increase	Eliminate

IV. BUCK CONVERTER MATHEMATICAL MODEL

Buck Converter is a step down DC-DC Converter. The output voltage is always less than the input voltage but with same polarity. Figure 3, shows the circuit diagram of a buck converter. The buck converter is a switched mode power supply and uses two switches (a transistor and a diode). The switching transistor S plays an important role to keep the output voltage of the converter at the desired value. The duty cycle (d) of the switch is given by,

$$d = \frac{v_o(s)}{v_{in}(s)} = \frac{t_{on}}{t_{on}+t_{off}} \tag{7}$$

Where, t_{on} is the time when switch S in on and t_{off} is thetime when switch S is off. d can vary in between 0 and 1.The duty cycle is applied by a Pulse Width Modulation (PWM) block. The governing equation of the buck operating in the continuous conduction mode can be represented by the following averaged steady state equation [13], [14].

$$\frac{di_L}{dt} = \frac{1}{L}(V_{in}d - i_L R_L - V_o) \tag{8}$$

$$\frac{dv_C}{dt} = \frac{1}{C}(i_L - i_{out}) \tag{9}$$

$$V_o = v_c + R_c(i_L - i_{out}) \tag{10}$$

Where, V_o is the output Voltage, V_{in} is the input voltage, i_L is the inductor current, i_{out} is the output current etc. Figure 3 shows the buck converter circuit.

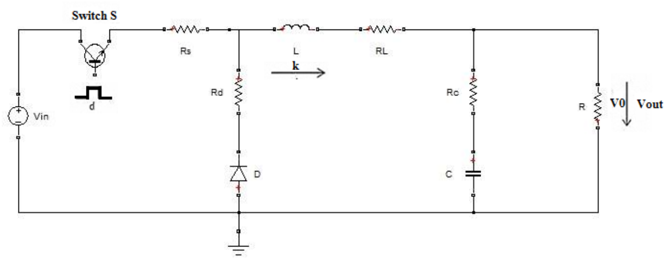

Figure 3. The buck converter circuit.

V. SIMULATION RESULTS

For the simulation, Matlab/ Simulink software was used. The Simulink model used for the simulation is shown in figure 4. The area covered by the blue rectangle contains the intelligent PI controller. The PWM block is used to generate the duty cycle of the switching signal. A saturation block was placed before the PWM block to saturate the controller output signal. The saturation block has two limits: Upper Limit which has a value 1 and Lower Limit which has a value 0. If the controller output signal is between the limits, the block has no functionality. However, if the controller output signal is not between the limits then the saturation block take its action and clip off the signal to either upper or lower limit. The parameters of the PI controller for the Intelligent PI controller is chosen randomly which comes from the theory of Intelligent PI controller presented in section II. For Classical PI controller, the tuning was done using the famous Ziegler-Nichols PID tuning rule. Figure 4 show the Simulink model of the Intelligent PI controlled PWM based buck converter.

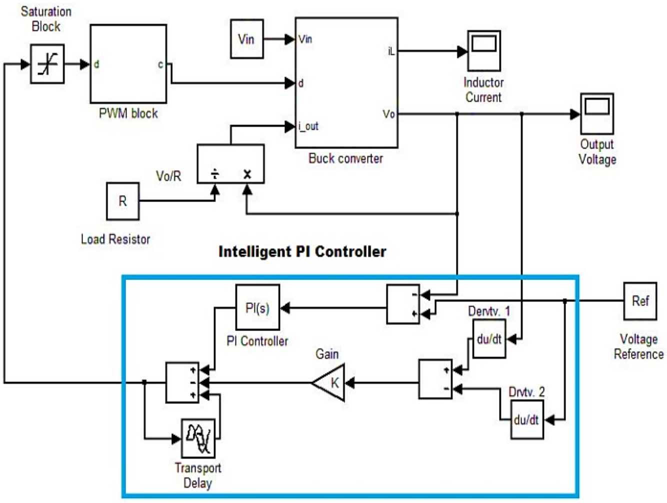

Figure 4. Simulink model of the Intelligent PI controlled PWM based buck converter.

Figure 5 shows the output response of the buck converter under consideration with classical PI controller. From figure1, it can be said that the controller has a very poor performance with very high settling time, peak overshoot and moderate steady state error. The output is always higher than the desired reference i.e. 2V, which indicates bad tracking performance. The comparison of output responses with classical and intelligent PI controller is shown in figure 2. The time domain performance of thess two controllers are given in Table 3. From figure 6, we can say that the Intelligent PI controller outperform the classical one in every aspect. It reaches to steady state value within (0.32ms) whereas the classical one took (2.8ms). The intelligent controller gives almost no or negligible overshoot, whereas the classical one gives a very high peak overshoot with respect to the desired reference of 2V. The steady state ripple voltage varies between 1.9995 & 2.0005V. The output response reach to very good performance level within a very short time and sustain the performance.

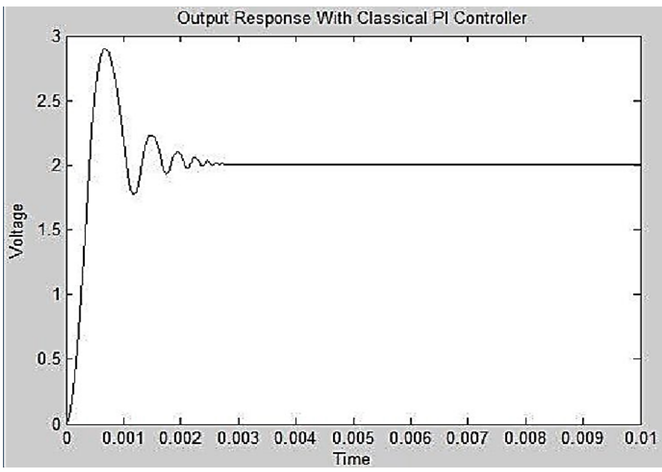

Figure 5. Output response ofClassical PI controlled PWM based buck converter.

Figure 6 shows the Comparison between the output responses of Intelligent and Classical PI controller.

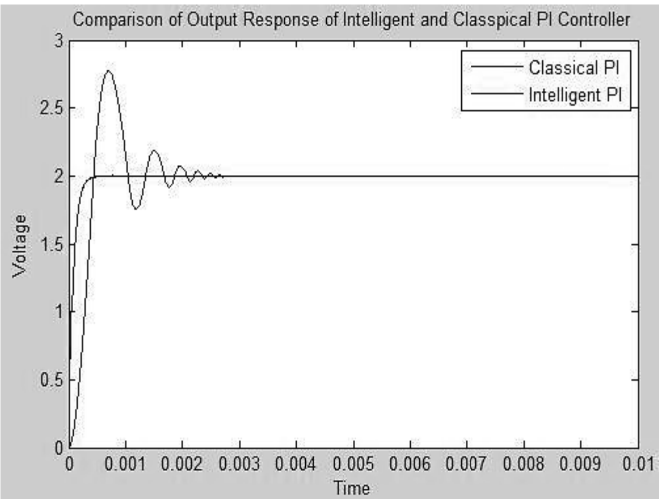

Figure 6. Comparison of output responses of Intelligent and Classical PI controller.

Figure 7 shows the performance comparison of the system with two different controllers under varying reference signal.

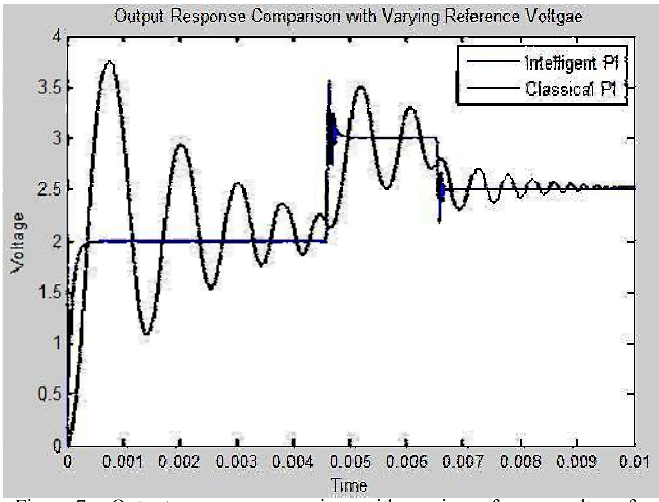

Figure 7. Output response comparison with varying reference voltage for classical and intelligent PI controlled buck converter.

This figure also tells about the superiority of the intelligent PI controller. The reference was set as 2 V from 0 to 4 ms, then 3V upto 6 ms and then 2.5V up to 10 ms. The system equipped with I-PI controller successfully tracked the reference with a very low settling time and almost negligible steady state error. It gave no, moderate and negligible peak overshoot for 3, 2.5 & 2 V reference signal respectively. In contrast to its intelligent counterpart, the classical one actually never been able to track the reference from 0 to 9 ms. After that it is close to the reference signal. From this the adaptiveness of the intelligent controller can be proved. Table 2 provides the overall time domain performance comparison between classical & intelligent pi controlled buck converter

TABLE II. COMPARISON OF TIME DOMAIN PERFORMANCES OF CLASSICAL& INTELLIGENT PI CONTROLLED BUCK CONVERTER

CL Performance	Rise Time (ms)	Settling Time(ms)	Maximum Peak Voltage(V)
Intelligent PI	0.17	0.32	2.0048
Classical PI	0.3	2.8	2.7725

VI. PRACTICAL DATA OF VARYING OUTPUT VOLTAGE

As the comparison of time domain performances are identified in Table II, for observing better mathematical significant figure more practical data can be accounted. In Table III Ripple calculation for PWM is included when the voltage is varied as 10%, 15% and 90% of maximum output voltage.

TABLE III. RIPPLE CALCULATION FOR PWM BY VARYING OUTPUT VOLTAGE

Max O/P	Performance Parameter	Rise Time (ms)	Settling Time (ms)	Max Peak Voltage (V)	PWM Generator
10%	Input current ripple	0.13	0.23	2.1048	0.014 A
	Output voltage ripple	0.3	2.0	2.6725	0.0046 V
15%	Input current ripple	0.19	0.38	2.3248	0.018 A
	Output voltage ripple	0.3	2.9	2.8725	0.0044 V
90%	Input current ripple	0.25	0.32	2.9848	0.032 A
	Output voltage ripple	0.3	3.2	3.1725	0.0054 V

It can be recapitulated that 90% maximum output voltage can be a better option that 10% or 15% maximum output voltage in this regard.

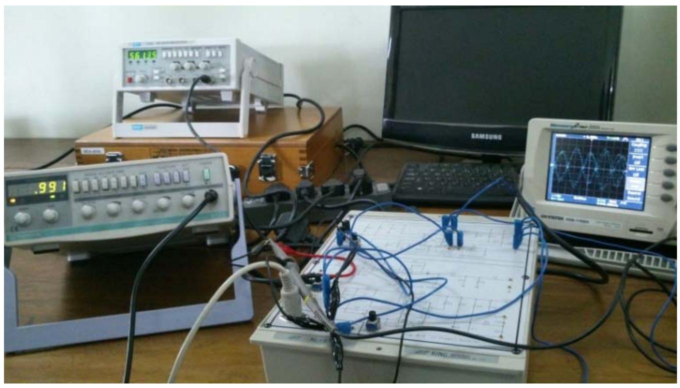

Figure 8. Output response comparison with varying reference and output voltage

In Figure 8, the partial experment equipments for varying output voltage is enclosed herewith. The datas are in Table III respectively.

VII. CONCLUSION

This paper describes the performance comparison of a classical PI and Intelligent-PI controlled DC-DC buck converter operating at 100 KHz switching frequency that convert an input signal of 5V into 2V output. The simulation result showed the superiority of the intelligent PI controller. The I-PI controller achieve the desired reference voltage with no or negligible overshoot, low settling time and other satisfactory time domain response properties. The system equipped with I-PI showed very good performance on varying reference signal compared to the system equipped with classical PI, Which gives an indication on the robustness of the I-PI control technique. The most important thing was designing the I-PI controller need no model of the plant to be controlled. This could make a revolution in the industrial control system as it is very difficult to obtain a complete dynamical model of the complex industrial process.

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