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# VOLTAGE REGULATOR USING A DC-DC CONVERTER CONTROLLED BY INTERPOLATED PI GAIN SCHEDULER FOR SOLAR CHARGE APPLICATIONS

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Abstract. *A voltage regulator, which is designed based on DC-DC converter topology and controlled with a non conventional adaptive interpolated PI gain scheduling controller, is presented in this paper. The proposed control method has been embedded on real microcontroller hardware and its performance has been tested under load change conditions and under input voltage variations. Some PI parameters are selected from a few explorations, where for some output voltage points, the minimum maximum overshoot and settling time is used to select the best PI pairs. An interpolation technique is then used to choose a representative PI parameter for each output voltage case in between. As a result, this semi adaptive control algorithm is simpler than the existing fully adaptive techniques. The testing results show that the PI control with the interpolated PI gain scheduling technique gives better transient response compared to the traditional fixed PI controller. The time domain transient response measurements, under load changes within the range of 20-1000 Ohm, present that the settling time value of the proposed control method is below 1.0 second, rise-time below 0.436 second, maximum overshoot below 0.5%, and the steady-state error below 0.3 V.*

**Keywords:** Power electronics, PI gain scheduling control, Adaptive control, Solar charge controller, Voltage regulator, Buck-boost converter

1. **Introduction.** Nowadays renewable energy has been a very important issue. The reductions of fossil fuels resources and environmental issue are among the reasons to accept the renewable energies as alternative energy sources. Solar energy is a primary energy resource for the earth. In order to convert the photon energy from the sunlight into electric energy, photovoltaic cells are then introduced. There are many research works in the world regarding the inventions of new technologies to improve the energy conversion from the sunlight. Certainly, in the future, as the conversion efficiency approximates 50% point, or even more than that value, the use of photovoltaic (PV) cells will grow rapidly.

Sunlight unfortunately appears only in days. In any circumstance, it will even appear only, when the sky is not covered by clouds. Due to such conditions, in the PV-based power generation systems, an energy storage system, such as rechargeable battery, is sometimes involved in the system. There are many battery chargers that can be found in markets. Some of them are used to charge a 12V-battery, where the electric energy source is taken from a single PV panel or interconnected PV panels. They are accordingly named as solar charger or solar charge controller.

This paper will present one of the functional units in a solar charge controller called voltage regulator. Voltages regulators (VRs) can be divided generally into linear regulator and switched-mode regulator. The latter VR type becomes more famous recently, due to

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its low power consumption. A voltage regulator is used to control or maintain a ripple DC input voltage to be stable, constant or near constant DC output voltage. Since signal conversion is made from DC to any other DC voltage level, this VR is also commonly called as DC/DC converter. In accordance with their conversion level ability, they are classified into buck (step-down) converter, boost (step-up) converter and buck-boost converter. Cuk and SEPIC (single-ended primary inductive converter) are other types of DC/DC converter, but can be classified as buck-boost converter. SEPIC converter is particularly used in high power applications where input-output voltage should be isolated to reduce harmonics [1].

A good quality solar charge controller is equipped with not only a voltage regulator unit, but also with a maximum power point tracer (MPPT) unit [2], and a state-of-charge estimator unit. Our research project will design such good quality solar charger prototype/product. However, those other units are not discussed in this paper. The MPPT unit is used to maximize power transfer from photovoltaic (PV) panels to the load. Since the output voltage levels of the MPPT unit vary over time, and the electric energy will be stored in a rechargeable battery, a voltage regulator is used to control the charge voltage rating.

This paper presents a simple new idea to a semi-adaptive interpolated proportional integral (PI) gain scheduling control technique. The simplicity of the control method can however provide acceptable performance over input variations and be better than the traditional static PI control method. In order to present the idea clearly, the paper is organized as follows. Related works and the paper's contribution are presented in Section 2. Section 3 presents the used buck-boost converter topology. Section 4 presents the description of the hardware, experimental setup, and the brief description about the embedded control program. Section 5 presents the testing results showing the positive impact of the proposed control algorithm over conventional or traditional fixed PI control. Finally, the results are concluded in Section 6.

## 2. **Related Works and Contribution.**

Digital PID controller in general can be used to control the voltage level of a DC/DC buck converter [3]. Furthermore, other converter topology with cascode structure can also be used to improve the output gain of the converter [4]. Both aforementioned works generally use a conventional PID controller. The conventional PID approach is difficult to achieve fast dynamic response over ripple input voltage and load changes [5]. Therefore, some non-conventional techniques are proposed to overcome the problems.

To control the output voltage level of a DC/DC converter having fast dynamic response over input and load changes, some existing control methods are proposed. Among those control methods, some of them are fuzzy logic control or combined (hybrid) fuzzy PID technique [6], combined PI control with fuzzy-neural [7], and combined PI control with multivariable robust H-Infinity method [8]. Another non-conventional technique is proposed in [9], where the controller directly controls the output voltage based on a particle swarm optimization (PSO) method. Hence, it requires no parameter searching subroutine as in classical controllers.

DC-DC converter can also be controlled using robust control techniques [10], or with any extension to be a robust decentralized control [11], and using sliding mode control [12], or combined PI control with sliding mode technique to be a dual loop control [13]. Other impressive control methods, which can be classified as semi adaptive control method, are gain scheduling technique [14], or combining PI control with the gain scheduling technique [15], etc.

We propose also a gain scheduling technique with a special contribution to a simple guide to self tune the PI gain control or parameters. The PI gains are adaptively scheduled based on the output voltage levels, which are achieved through a simple interpolation equation. Fuzzy, hybrid fuzzy, PSO-based or sliding mode controllers though can effectively provide fast transient response. However, the achieved control algorithms are more complex. Our proposed algorithm can be simply embedded in a microcontroller with short control program subroutine compared to the other non-conventional control methods.

## 3. Circuit Topology.

The circuit topology of the switched mode DC-DC converter used in our hardware is presented in Figure 1. The DC/DC converter can be operated in two operation modes, namely discontinuous and continuous conduction mode [16]. An electronic switch is implemented using an N-channel MOSFET (NMOS), where the ON/OFF states of the switch are activated by a PWM signal through its gate (G) terminal. The output voltage level ($V_O$) of the DC-DC converter can be controlled by varying the duty ratio of the PWM signal. The duty ratio is obtained by comparing the saw-tooth signal ($V_{SAW}$) with the control signal ($V_{CTRL}$) generated by the PI gain scheduler. The PWM signal ($V_{PWM}$) will be ON as $V_{CTRL} > V_{SAW}$ and will be OFF as $V_{CTRL} \leq V_{SAW}$. This $V_{PWM}$ will be applied to the NMOS gate terminal after power amplification using an NMOS driver device.

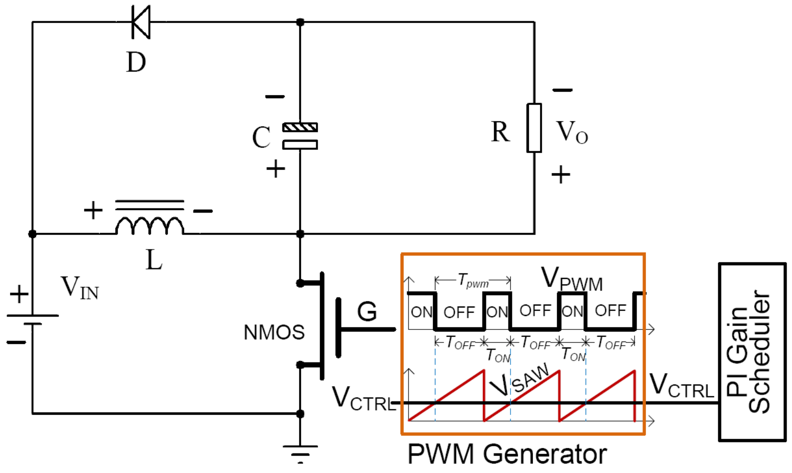


Figure 1. The topology of the buck-boost converter circuit

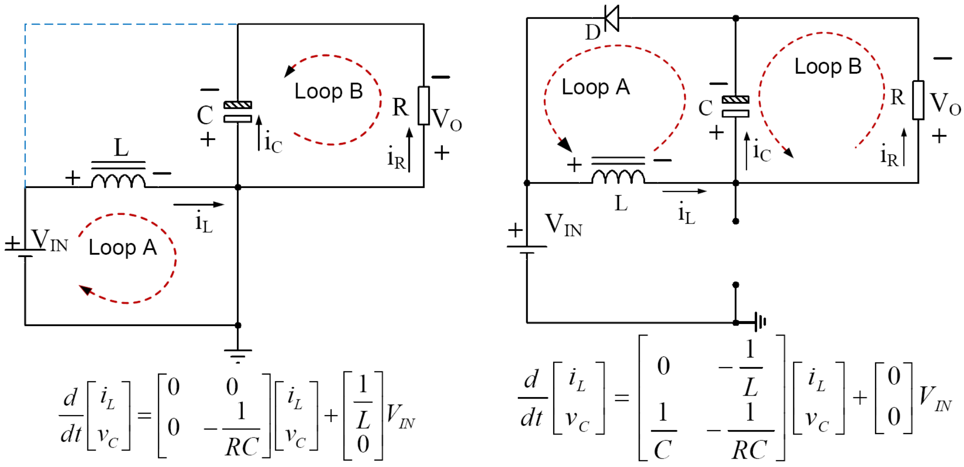
The DC/DC converter works based on the following descriptions. As shown in Figure 2(a), when logic ‘1’ is set to the NMOS gate terminal, then the NMOS will be ON. In this case, the diode $D$ is reverse biased. Hence, the input voltage ($V_{IN}$) will be directly connected to the inductor $L$. The electric energy is accumulated and stored in $L$ accordingly. At the same time, the capacitor $C$ will be discharged, and the electric energy will be supplied to the load.

As shown in Figure 2(b), when logic ‘0’ is set to the NMOS gate terminal, then the NMOS will be OFF. In this case, the voltage source is isolated from the system. The diode $D$ is forward-biased. Hence, the electric energy is discharged from the inductor $L$ to charge the capacitor $C$ and to the load, concurrently. The state-spaces equation for each ON or OFF state of the NMOS is presented also in the figure.

## 4. Hardware, Experimental Setup and Embedded Control Software.

### 4.1. Hardware and experimental setup.

After the hardware has been realized, then an experimental setup is built. Figure 3(a) shows the block diagram of the system testing. A host computer is utilized to install a software used to capture the output voltage in real time, especially the transient-time response. For instant output voltage measurement, an LCD is also installed in the test configuration, which is used to observe the steady state output voltage.



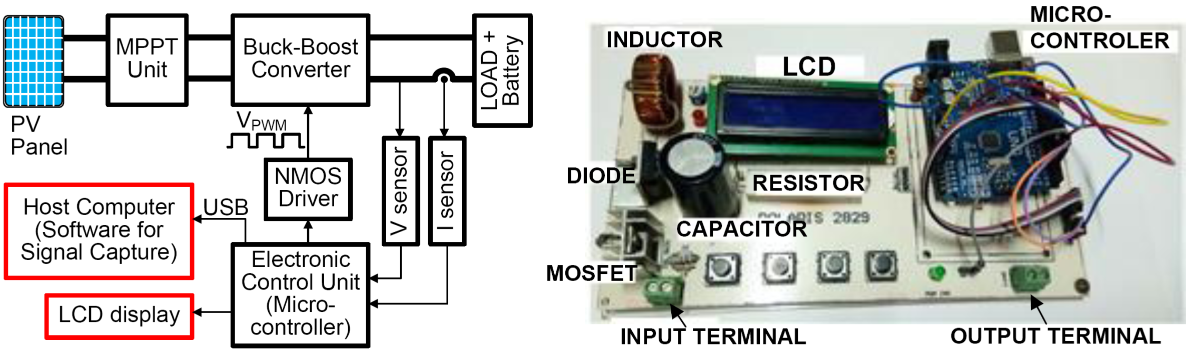
$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_C \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix}\begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{IN}$$

(a) NMOS Switch ON

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_C \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}\begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{IN}$$

(b) NMOS Switch OFF

FIGURE 2. Current loops as the MOSFET switch is (a) ON and (b) OFF



(a) Hardware block diagram

(b) Real hardware photograph

FIGURE 3. (a) The block diagram of the experimental setup, and (b) the photograph of the buck-boost converter hardware

The photograph of the real hardware of the buck-boost circuit and the electronic control unit (ECU) is depicted in Figure 3(b). The ECU is implemented using a microcontroller and is used to generate a PWM signal that is applied to the NMOS gate terminal. A voltage sensor and current sensor are used to measure the voltage and current at the converter output terminal. In the current work, only the voltage sensor is used. The current sensor was installed in the hardware for extension utilization such as power quality analysis.

4.2. **The embedded control program.** The PI control program is embedded on the microcontroller unit. The PI parameters, i.e., proportional $K_P$ and integral $K_I$ gain, are scheduled based on an interpolation equation.

Table 1 presents the selected relatively better PI values, where the $K_P$ and $K_I$ values are obtained from the PI parameter explorations. In the parameter exploration, some PI parameters are selected. For some output voltage points, the PI pairs giving the minimum values of the maximum overshoot and settling time are chosen. The selected $K_P$ and $K_I$

TABLE 1. The relatively better $K_P$, $K_I$ values selected from the PI explorations

| $V_O$ | 1 V | 3 V | 5 V | 7 V | 9 V |
|---|---|---|---|---|---|
| $K_P$ | 1.3 | 1.3 | 1.7 | 2.0 | 2.0 |
| $K_I$ | 36 | 36 | 30 | 18 | 20 |

values, presented in Table 1, are used to generate an interpolation function, where the output voltage $V_O$ is chosen as the independent variable. The interpolated function for the proportional control parameters ($K_P$) is presented in Equation (1). While, Equation (2) presents the interpolation function for the integral control parameters ($K_I$).

$$K_P(V_O) = -0.0013V_O^4 + 0.017V_O^3 - 0.087V_O^2 + 0.38V_O + 0.99 \tag{1}$$

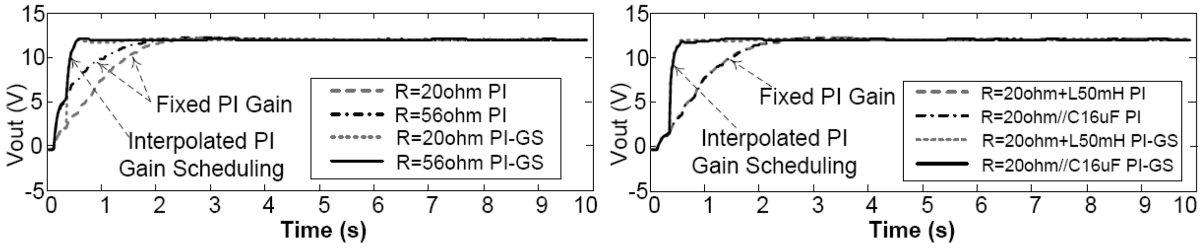
$$K_I(V_O) = 0.021V_O^4 - 0.25V_O^3 + 0.042V_O^2 + 2.1V_O + 36.0 \tag{2}$$

The above equations are then implemented in C/C++ software program and embedded in a microcontroller. The achieved subroutine control program is simple. In order to see the real performance of the proposed control algorithm, we have made a real in-circuit testing as presented in the following section.

## 5. The Testing Results.

This section presents the testing results directly from the controlled buck-boost converter hardware. Three testing schemes are presented, i.e., testing under different load conditions, testing under runtime load change conditions and testing under input voltage change conditions.

Figure 4 presents the testing results under 2 load configurations. In this testing scheme, the transient response and steady state response of the converter's output voltage are observed. Two load configurations are used in the testing scenarios, i.e., pure resistance load, and the RL-series as well as the RC-parallel loads. Figure 4(a) shows the comparison results for the output voltage of the converter controlled using the traditional fixed PI gain control and using the proposed adaptive PI gain scheduling (PI-GS) control method, where two different pure resistance load values are chosen. Figure 4(b), meanwhile, shows the other results by using two combined RL-series and combined RC-parallel. It seems that the adaptive PI-GS control method gives better performance figures compared to the fixed PI control method, both in terms of the maximum overshoot and the settling time.



(a) (b)

Figure 4. The testing results of the fixed and adaptive PI gain under 2 load configurations

Figure 5 presents the testing results for under 4 runtime load change conditions, where the resistance load value is changed at about 6th seconds after the initial testing time. Four testing schemes for down changing are made, i.e., the load changes from 56 Ω down to 20 Ω, from 56 Ω down to 50 Ω, from 100 Ω down to 56 Ω, and from 220 Ω down to 100 Ω. Meanwhile, four testing schemes for up changing are also made, i.e., the load changes from 20 Ω up to 56 Ω, from 50 Ω up to 56 Ω, from 56 Ω up to 100 Ω, and from 100 Ω up to 220 Ω. Figures 5(a) and 5(c) show the results of the load decrements and the load increments, respectively, when using the fixed PI gain, while Figures 5(b) and 5(d) present the results of the load decrements and the load increments, respectively, when using the interpolated adaptive PI gain scheduling (PI-GS) technique. It seems that the adaptive PI-GS technique gives better time domain characteristics, i.e., lower maximum overshoot and lower settling time compared to the traditional fixed PI gain control.

The testing results under input voltage change condition are illustrated in Figure 6. The input voltage of the buck-boost converter is changed within the range of 9 V and

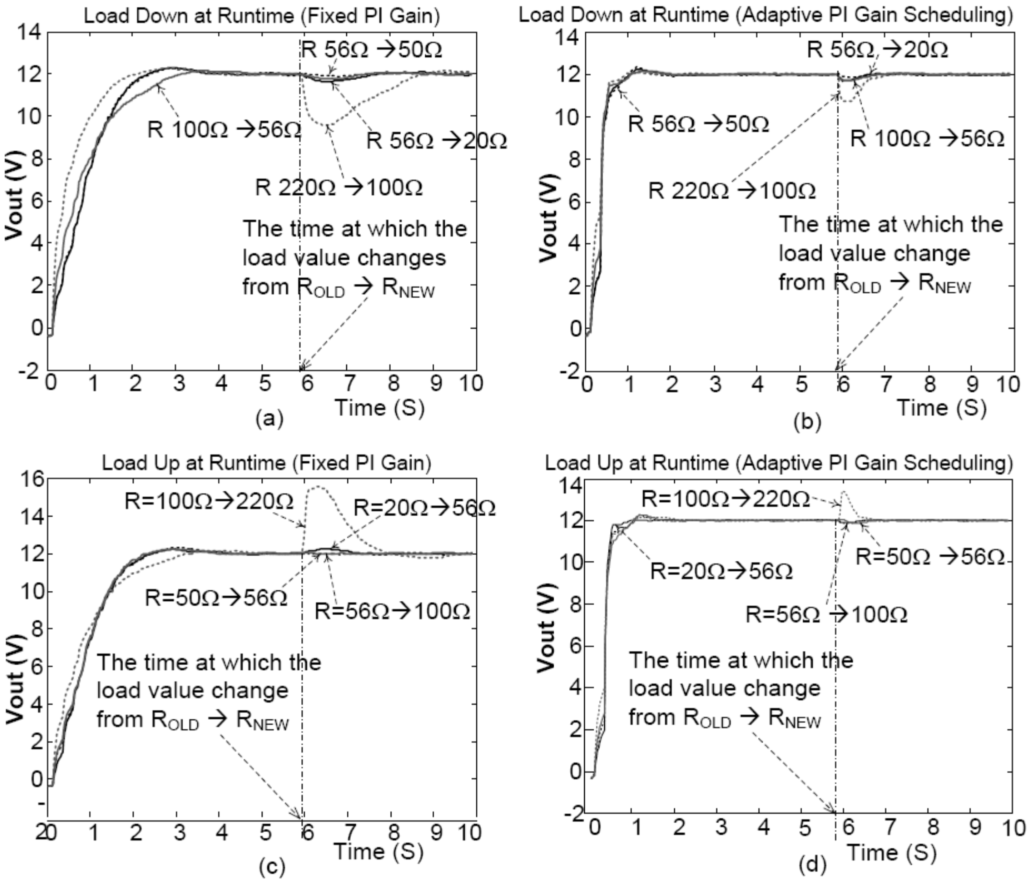
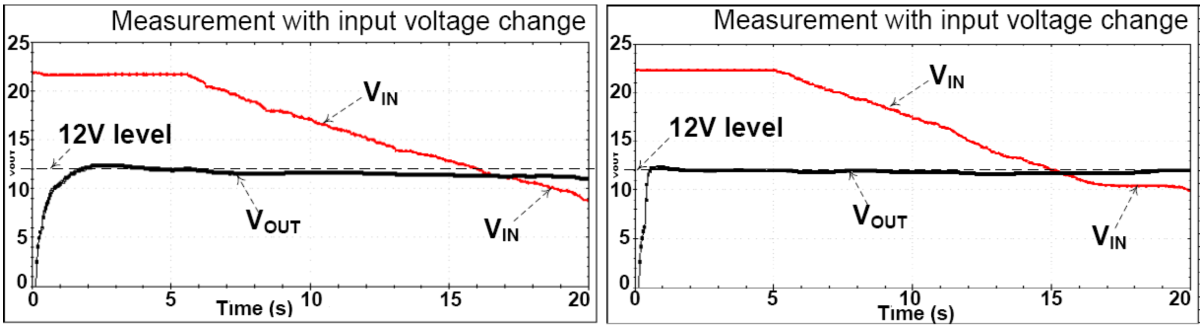


Figure 5. The testing results of the fixed and adaptive PI gain under 4 runtime load change condition



(a) Fixed PI gain (b) Interpolated PI gain scheduling

Figure 6. The testing results of the fixed and adaptive PI gain under input voltage change condition

22 V. The input voltage is firstly set to 22 V and kept constant until the 5th or 6th, and then it is gradually dropped to about 8 V/9 V. Figure 6(a) shows the testing results for the fixed PI gain control method, while Figure 6(b) presents the testing results for the adaptive PI-GS method. The performance of the adaptive PI-GS looks better than the fixed PI control technique, especially in terms of the steady-state error. The fixed PI gain control cannot maintain the output voltage at the expected 12 V, after the input voltage starts to drop. The adaptive PI-GS control method meanwhile can stabilize the output voltage at about 12 V as expected, although the input voltage levels change at runtime.

6. **Conclusion.** This paper has presented the adaptive interpolated PI gain scheduling technique used to control the output voltage level of a buck-boost converter. The buck-boost converter is used to maintain the voltage level of the solar charge controller, where the input voltage may vary due to the variation of the solar irradiance. Although the experiments are made for 12 V voltage regulation in the 12V-PV-battery, the proposed technique can also be used for other expected voltage levels.

The proposed technique outperforms the conventional PI controller. Based on our experimental testing, the conventional PI controller cannot respond well to the dynamic changes of the input voltage. In steady state time domain, the conventional PI control cannot maintain well the expected output voltage level. Based on particular experiments, in general, the proposed control algorithm gives settling time value below 1.0 second, rise-time below 0.436 second, maximum overshoot below 0.5%, and the maximum steady-state error ripple below 0.3 V. Those time domain specifications are in general acceptable for good quality prototype.

In the future, this voltage regulator with the interpolated PI gain scheduling control unit will be integrated with a maximum power point tracer (MPPT) unit and battery state-of-charge (SoC) estimation unit. The input terminal of the voltage regulator unit will be connected to the output terminal of the MPPT unit. Design, implementation and testing of the solar charge controller that consists of the aforementioned units are exciting future works with more comprehensive analysis results on the overall system characteristics. Design optimization of the control algorithm is also an interesting outlook.

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