

Adaptive Interpolated PI Gain Scheduling for Voltage Regulator in Solar Charge Controller Applications

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Abstract. Buck-boost converter is one of the dc-dc converter that can both increase and decrease the value of output voltage. Due to its wide output range, this converter is very appropriate for using in solar-based electric generation systems. To control the stable expected output voltage, this converter is usually integrated with feedback control. One of the old and widely used control techniques is PID control. However, conventional PID controls still have deficiencies, because the parameters of PID parameters are static so that for wide ranges of input or load will provide different transient responses. This paper will present a new PI control with an adaptive interpolated PI gain scheduling technique. The proposed control algorithm has been embedded and implemented in real microcontroller hardware and its performance has been tested under load change conditions, and the input voltage changes within the range of 8-22 V. Testing results show that PI control with gain scheduling technique produces 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 proposed control algorithm give settling time value below 1.0 second, rise-time below 0.436 second, maximum overshoot below 0.5%, and the steady-state error below 0.3 V.

1 Introduction

Recently, renewable energy has been discussed as a very important issue in many energy forums. The fossil fuels resources reduction and environmental issue are considered to be reasonable to extensively use renewable energies. One of primary energy resources in the earth is the solar energy. A device called solar or photovoltaic cell is used to convert the photon energy from the sunlight into electric energy. Many research works focusing on the inventions of new technologies especially new materials to improve the energy conversion efficiency of the sunlight. As the conversion efficiency of the solar cells approaches 50% in the future, or even over, the PV use will surely increase rapidly.

The appearance of sunlight can be seen only in daytime. Due to any situation, such as clouds covering the sky, the sun penetration to the earth is not maximal. Therefore, the solar energy should be stored in a rechargeable battery installed in the system for further use e.g. at night. In markets we can find many battery charger units with different specifications. Some of them have a 12V-voltage rating specification. Since the electric energy is harvested from a single PV panel or multiple interconnected PV panels, then this unit is called as solar charger or solar charge controller.

This paper will present one of the functional units in a solar charge controller called voltage regulator. Voltage regulators (VRs) can be divided generally into

linear regulator and switched-mode regulator. The latter VR type becomes more famous recently, due to 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 charge controller having good quality should contain not only a voltage controller or regulator unit, but also with a maximum power point tracker (MPPT) unit [2], and a state-of-charge estimator (SoCE) unit. We have a plan to design a good quality solar charger prototype/product. Nevertheless, both units, the MPPT and SoCE units are not presented in this paper. The MPPT unit has function to maximize power transfer from PV panels to the battery or load. Because the level of the MPPT's output voltage changes over time, and the electric charge will be stored in a battery or accumulator, then to control the charge voltage at certain rating a voltage regulator is required.

2 Related works and contribution

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

There are some techniques that can be used to control the output voltage level of a DC/DC converter with fast dynamic response over input and load change condition. Among those existing techniques, we can mention some of them such as fuzzy logic control or combined fuzzy PID technique, fuzzyneural PI control method [6], Multivariable robust H-Infinity PI control [7], Robust decentralized control [8], sliding mode control technique [9], gain scheduling technique [10], [11], etc. We propose also a gain scheduling technique with a special contribution to a simple guide to self-tune the PI control gain or parameter. The PI gains are adaptively scheduled based on the output voltage levels, which are achieved through an interpolation equation. The proposed algorithm can be simply implemented in a digital PID control subroutine.

In order to expose the idea clearly, we organize the paper as follows. Section III presents the use buck-boost converter topology. Section IV presents the description of the hardware, the brief description about the embedded control program, and the testing or experimental set up. To expose the positive impact of the proposed control algorithm, the comparative study with conventional or traditional fixed PID control is presented in Section V. Finally, the results are concluded in Section VI.

3 Circuit topology

Fig. 1 presents the topology of the used switched mode DC/DC converter in our hardware. The DC/DC converter can be operated in discontinuous and continuous conduction mode [12]. A PWM signal is applied to the gate (G) terminal of the n-channel MOSFET. The output voltage level (V_O) can be controlled by varying the duty ratio of the PWM signal.

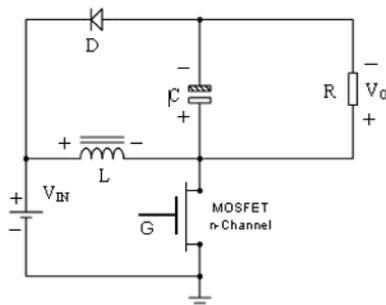
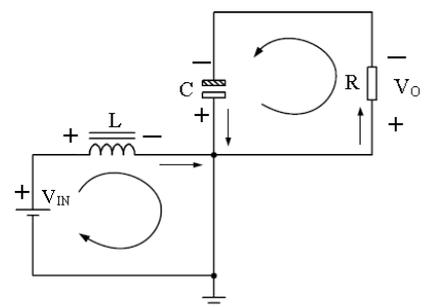


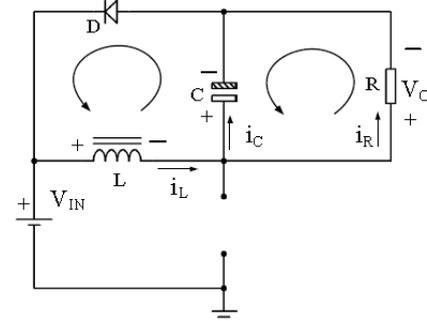
Fig. 1. The topology of the buck-boost converter circuit.

The working principle of this DC/DC converter is as follows.

- When logic '1' is applied to the gate terminal of the MOSFET, then it will be ON, as presented in Fig. 2(a). In this condition, 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 moment, the capacitor C will discharge the electric energy and supply it to the load.
- When logic '0' is applied to the gate terminal of the MOSFET, then it will be OFF, as presented in Fig. 2(b). In this condition, the voltage source is disconnected 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.



(a) NMOS is switched ON



(b) NMOS is switched OFF

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

4 The circuit hardware and embedded software

4.1 The electronic circuit hardware

We have designed the buck-boost circuit topology and the electronic control unit in hardware as presented in Fig. 3. A microcontroller unit is used to generate a PWM signal for the gate terminal of the n-channel MOSFET. We use a voltage sensor and current sensor to measure the output voltage and current. In our current work, we use only the voltage sensor. Although the current sensor has not been used, it was installed in the hardware for future use and extended analysis such as output power quality measurement.

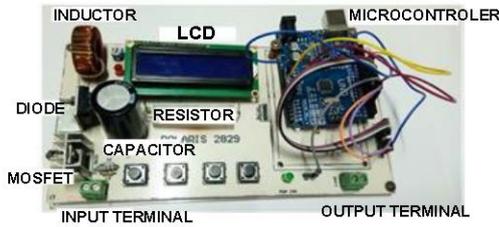


Fig. 3. The photograph of the buck-boost converter hardware.

4.2 The embedded control software

The PI control program is embedded on the microcontroller unit. The PI parameter, i.e. proportional KP and integral KI gain are scheduled based on a interpolation equation. Table I presents the selected relatively better PI values. The KP and KI values are obtained from the experiments.

Table 1. The selected relative better PI parameter values.

VO	KP value	KI value
1 V	1.3	36
3 V	1.3	36
5 V	1.7	30
7 V	2.0	18
9 V	2.0	20

The KP and KI values, presented in the Table I, are interpolated as function of the VO variable. The interpolated functions for both PI parameters are shown in Eq. (1) and Eq. (2), respectively for the proportional and integral control parameters.

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

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

4.3 Experimental setup

After the hardware has been realized, then an experimental set up is built. Fig. 4 shows the block diagram of the testing system. A host computer is utilized to install a software used to capture the output voltage in real-time, especially the transienttime response. For instant output voltage measurement, an LCD is also installed in the testing system. It is used to observe the steady state output voltage.

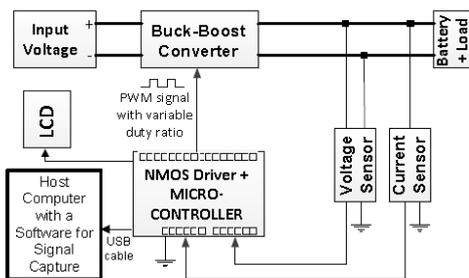


Fig. 4. The photograph of the buck-boost converter hardware.

5 Experimental 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.

Fig. 5 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 resistive load, and the RL-series as well as the RCparallel loads.

Fig. 5(a) shows the comparative 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. Fig. 5(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 give better performance figures compared to the fixed PI control method, both in terms of the maximum overshoot and the settling time.

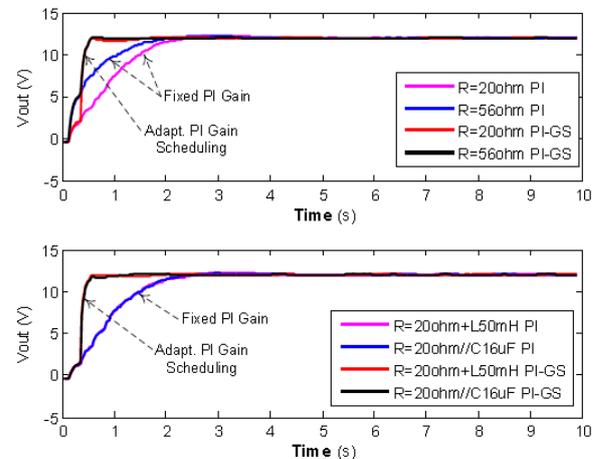


Fig. 5. The testing results of the fixed and adaptive PI gain under 2 load configurations.

The testing results under input voltage change condition are illustrated in Fig. 6. The input voltage of the buck-boost converter is changed within the range of 9 V and 22 V. The input voltage is firstly set to 22 V and are kept constant until the 5th or 6th, and then it is gradually dropped to about 8 V/9 V. Fig. 6(a) shows the testing results for the fixed PI gain control method, while Fig. 6(b) presents the testing results for the adaptive PI-GS method.

The performance the adaptive PI GS looks better than the fixed PI control technique, especially in term 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 testing.

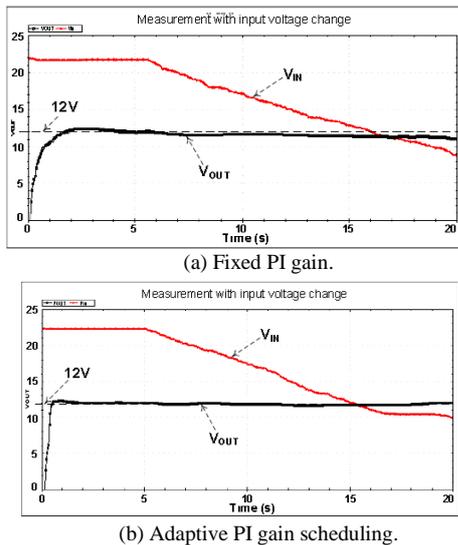


Fig. 6. The testing results of the fixed and adaptive PI gain under input voltage change condition.

6 Conclusions

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 radiance. 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 response well 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 give 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 0.3V. Those time domain specifications are in general acceptable for good quality prototype.

In the future, we will develop a complete product of solar charger by combining it with our previously investigated MPPT module [2].

We gratefully acknowledge the Ministry for Research, Technology and Higher Education of the Republic of Indonesia for funding and supporting our research work under the scheme of "Post-Graduated Collegium Research Grant" (*Hibah Penelitian Tim Pasca Sarjana*) in the year 2017 and 2018.

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