Control Engineering Practice 77 (2018) 127–137

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Current sensorless finite-time control for buck converters with time-varying disturbances☆

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ARTICLE INFO

Keywords:
Disturbed buck converter
Current sensorless
Finite-time control
Time-varying disturbances
Disturbance rejection

ABSTRACT

DC–DC buck converters are widely adopted to feed power from renewable energy distributed generators into smart grids. Sliding mode control (SMC) schemes enable such converter systems to inject high-accuracy voltage and current into the connected devices or loads, which are of good robustness in dealing with matched disturbances and model uncertainties. However, the chattering phenomenon, caused by the discontinuous control law, leads to large ripples in output voltage and increases switching losses. Moreover, in current sensor failure cases, conventional state feedback control law is not available for higher control performance. In this research paper, a recursive design based universal finite-time observer (UFTO) is applied to reconstruct the current information and lumped disturbances simultaneously, which provides an active disturbance rejection approach. Then, a non-singular sliding mode control based current sensorless finite-time control strategy is developed for the converter system to improve the transmit behaviours, control accuracy, and fault tolerance ability in the presence of various time-varying disturbances. As compared with traditional PID and existing asymptotical current sensorless approaches, both finite-time convergence property of voltage tracking error and active suppression ability against time-varying disturbances are obtained. A rigorous analysis on robustness stability has been provided for the proposed current sensorless finite-time control method. Experimental results are explored to comprehensively illustrate the feasibility and effectiveness of the proposed strategy.

1. Introduction

Along with the development of smart grids and renewable energy systems, the PWM based DC–DC converters have became one of the crucial elements in the process of power conversion. Moreover, high-performance converters are demanded in several practical industrial applications, such as solar photovoltaic systems (Li & Wolfs, 2008), electric vehicle (EV) systems (Ding, Liu, & Zheng, 2017; Ni, Patterson, & Hudgins, 2012), and distributed generation (DG) systems (Pahlevaninezhad, Drobnik, Jain, & Bakhshai, 2012; Sun & Gao, 2005). The accurate regulations of output voltage and current are of significant importance in obtaining satisfying performance for the connected loads or devices (Yang, Wu, Li, & Yu, 2016). Prominent properties, including rapid dynamic response, offset-free tracking error, strong disturbance rejection ability, and fault tolerance ability should be guaranteed in the higher-performance DC–DC converter systems. Therefore, large amounts of interests have been aroused from both automatic control designers and power electronic engineers to improve the control performance.

It is well known that the control performance of converter system is always severely affected by various sources of parameter uncertainties and external disturbances, e.g. circuit parameter perturbations (Yang et al., 2016), load resistance variations (Cheng et al., 2017; Sun, Yang, Zheng, & Li, 2016), input voltage fluctuations (Wang, Li, Wang, & Li, 2017), etc. For example, in DG and EV systems (Ni et al., 2012; Pahlevaninezhad et al., 2012; Sun & Gao, 2005), there could be a wide range of load variations from free load to full load. Another example is that the output voltage of solar photovoltaic system is highly dependent on the variations of light intensity, which causes input voltage fluctuations in the connected converters (Li & Wolfs, 2008; Wang et al., 2017). In addition, the fault tolerance ability and cost of the whole system also have to be considered. The cost increases significantly due to the requirements of wideband current sensors. With the growing number of current sensors, the probability of malfunctions

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☆ This work is supported in part by the National Natural Science Foundation (NNSF) of China under Grants (61473080), and Scientific Research Foundation of Graduate School of Southeast University (YBJJ1766).

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https://doi.org/10.1016/j.conengprac.2018.05.014
Received 1 February 2018; Received in revised form 28 May 2018; Accepted 30 May 2018

is increasing at the same time, leading to the recession of system reliability (Giri, Maguiri, & Fadil, 2011; Ni et al., 2012; Zhang et al., 2014). However, in the design process of the existing current sensorless control, state observers are usually applied to reconstruct the current information without considering disturbances and model uncertainties. When considering the piratical converter systems, these conventional current sensorless solutions will have difficulty in obtaining satisfying control performance.

Sliding mode control (SMC) schemes enable the converter systems to inject high-accuracy voltage and current into the connected devices or loads, which are of good robustness in dealing with matched external disturbances and model uncertainties (Li, Yu, Fridman, Man, & Wang, 2017; Pastor et al., 2013; Shtessel, Edwards, Fridman, & Levant, 2013; Tan, Lai, & Tse, 2006). In the converter systems, finite-time convergence SMC approaches are investigated (Komurcugil, 2013; Wang, Li, Yang, Wu, & Li, 2016) to improve the transient responses of voltage and current. Results have shown that faster convergence speed, higher tracking accuracy, and better disturbance rejection ability can be obtained as compared with the corresponding asymptotically stable SMC methods (Feng, Yu, & Man, 2002; Li et al., 2017; Shtessel et al., 2013). However, due to the existence of discontinuous sign function, chattering phenomenon gets more adverse as switching gain becomes larger (Basin, Panathula, Shtessel, & Ramirez, 2016; Yang, Li, Su, & Yu, 2013). In practical digital implementations (Banerjee, Kotecha, & Weaver, 2016), the discrete sign function may lead to high frequency and high amplitude oscillations in the control input, which may even result in system's instability. Large amounts of ripples in the output voltage are caused. Super-twisting (STW) algorithm offers a continuous controller with the property of finite-time convergence to the designed sliding mode manifold (Chalanga, Kamal, Fridman, Bandyopadhyay, & Moreno, 2016; Davila, Fridman, & Levant, 2005). However, for the system whose relative degree is more than one, only the asymptotic convergence property of tracking error can be obtained (Li et al., 2017; Shtessel et al., 2013). Addressing it, the idea of non-singular terminal sliding mode (NTSM) methods have been developed (Feng et al., 2002; Yang et al., 2013; Yu, Yu, Shirinzadeh, & Man, 2005), which realize the finite-time convergence property of tracking error. With significant demands on both fast transient response and continuous property, it is imperative to develop a continuous finite-time controller incorporating advantages together.

In this research paper, attentions are focused on the current sensorless finite-time control design for disturbed buck converters in the presence of time-varying disturbances. A novel universal finite-time observer (UFTO) is designed to reconstruct current information and lumped disturbances. Then, a continuous finite-time control law is obtained based on estimations provided by the designed observer. Advantage complementarity is achieved in the proposed composite controller, in which both the dynamic and static performance of the converter system are considered. The major remarkable features are concluded as follows:

- Finite-time convergence property of the voltage tracking is obtained in the proposed continuous NTSM control approach. As compared with conventional SMC approaches, faster convergence rate and higher tracking accuracy can be obtained. Moreover, smaller control gains can be selected to suppress the effects of large uncertainties and disturbances in the continuous control law, which can avoid the severe control chattering and overlarge control amplitude.
- Active disturbance rejection ability can be obtained in the proposed controller. The parameter uncertainties, unmodelled dynamics, and external time-varying disturbances are regarded as the lumped disturbances. By using the proposed universal finite-time observer, an active and accurate remedy to the effects of time-varying disturbances is provided. Disturbances are compensated without introducing additional adverse effects, which provides a promising approach for trading off between the nominal performance and robustness.
- The fault tolerance ability can also be improved in the proposed controller. As compared with existing current sensorless approaches, the proposed universal finite-time observer can provide an accurate estimation of current information in the presence of external disturbances and parameter uncertainties. A reliable current sensorless running mode can be provided for the converter system. In this way, the cost of the whole system is decreased by reducing the physical current sensors.

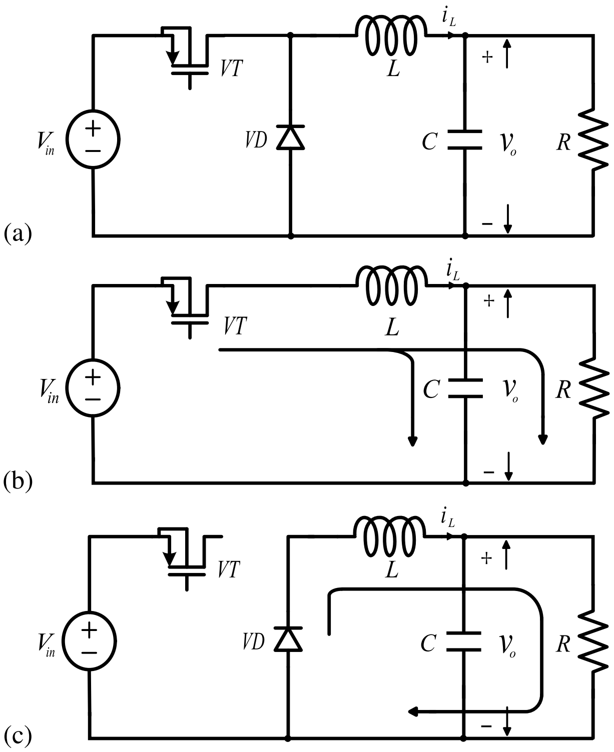

Fig. 1. Circuit diagram of buck converter. (a) An average case. (b) A switch ON case. (c) A switch OFF case.

Experimental verifications of the proposed control scheme on a DC–DC buck converter system are carried out to demonstrate the feasibility and effectiveness in the presence of various time-varying disturbance scenarios. By analysing the results, it is convincing that the proposed current sensorless approach exhibits superior robustness against time-varying disturbances compared with traditional PID, existing asymptotical current sensorless approaches, and the reported NTSM control solutions. It can also provide a reliable current sensorless running mode for the converter systems in practical applications.

2. System description and problem formulation

A typical PWM based DC–DC buck converter circuit is illustrated in Fig. 1, which comprises a DC voltage supply source V_{in}, a PWM driven switch device VT, a diode VD, a filter inductor L, a capacitor C, and a load resistance R.

By applying an averaging method and assuming slow variations for the signals of interest over a switching period, the average model is obtained and given as follows:

$$\begin{cases} \dot{v}_o = \dfrac{i_L}{C} - \dfrac{v_o}{RC}, \\ \dot{i}_L = \dfrac{uV_{in}}{L} - \dfrac{v_o}{L}, \end{cases} \tag{1}$$

where v_o and i_L here are the values of the capacitor output voltage and inductor current, respectively. The duty ratio $u \in [0, 1]$ denotes the