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Precise tracking of highly nonlinear phase-shift full-bridge series resonant inverter via iterative learning control

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ABSTRACT

This paper presents iterative learning control of the phase-shift full-bridge series-resonant inverter (PSFB-SRI). It has the merits of high conversion efficiency, medium-to-high power capacity, compact size, and low current–voltage stress on components, but the demerits of highly nonlinear dynamics that varies in a wide range depending on the operating points. The PSFB-SRI also suffers from a grid-voltage disturbance when it operates in grid-connected environment. To overcome these control problems, an iterative learning controller (ILC) supplemented with a proportional controller is developed and applied to the PSFB-SRI. Conventional proportional controller is used to improve the output current tracking performance. The ILC makes use of both previous-cycle and current-cycle learning terms which help the system output to converge to the reference trajectory. It is also simple in structure and easy to implement in practical applications. First-harmonic approximation of the PSFB-SRI model has been conducted and the resulting nonlinear large-signal model was used to construct the developed ILC. A detailed design guideline of the control parameters is provided. Numerical simulations validate the proposed control scheme, and experiments using a 500-W prototype demonstrate its feasibility.

1. Introduction

Due to the environmental concerns on global warming, fossil fuel exhaustion, the use of alternative energy has drawn significant attention. In the alternative energy systems (e.g., photovoltaic, thermo-electric), the small-scale and modular energy conversion devices generate electric power from the primary power sources; the outputs of these devices are combined with module-integrated converters (MICs) to deliver the rated power to the utility grid. The MIC enables individual operation of each module and reduces power losses caused by mismatch among modules. In addition, it allows ease of maintenance because it prevents system malfunction due to single-point failure and provides plug-and-play features. With these advantages, the MIC concept has become the trend for development of future alternative energy systems (Ghaffari, Seshagiri, & Krsti, 2015; Li & Wolfs, 2008; Pan, Cheng, Lai, & Chen, 2015).

The acceptability of the MIC is evaluated by conversion efficiency, power capacity, size, and reliability. In particular, recent increase in the power capacity of energy-conversion modules has stimulated the research to increase of the power capacity of the inverter circuits (Williams, Steele, & Reed, 2012). Considering these requirements, the phase-shift full-bridge series-resonant inverter (PSFB-SRI) with unfolding circuitry would be an excellent candidate due to its high conversion efficiency, medium-to-high power capacity, compact size, and low current–voltage stress on components (Nayanasiri, Vilathgamuwa, & Maskell, 2013; Trubitsyn et al., 2010).

However, the dynamic model of the PSFB-SR topology has hard nonlinearities such as the signum and the absolute-value functions. To overcome this problem, a number of researchers have proposed various control strategies. Based on the reduced balanced model and taking account of the zero-order hold delay and the computation delay in the sampled data system, a digital proportional–integral (PI) controller with notch filter is designed (Zheng & Czarkowski, 2007). Then, the controller is derived using passivity theory which ensures that the closed-loop system is exponentially convergent (Carrasco, Galvan, Valderrama, Ortega, & Stankovic, 2000; Kim & Youn, 1991; Lu, Cheng, Ho, & Pan, 2005). To improve the dynamic performance of the converter system, the quasi-current mode control, which indirectly regulates the resonant current, is developed (Lu, Cheng, & Ho, 2008). Next, a control-oriented dynamic model, which appropriately describes the large-signal behavior of the power circuit by average state variables, is developed. Using input–output feedback linearization, a control design methodology is then presented, which leads to a family of sliding surfaces that make the output voltage behave following a particular large-signal linear dynamics (Castilla, de Vicuna, Guerrero, Matas, & Miret, 2005). Recently, an adaptive output feedback controller, involving online

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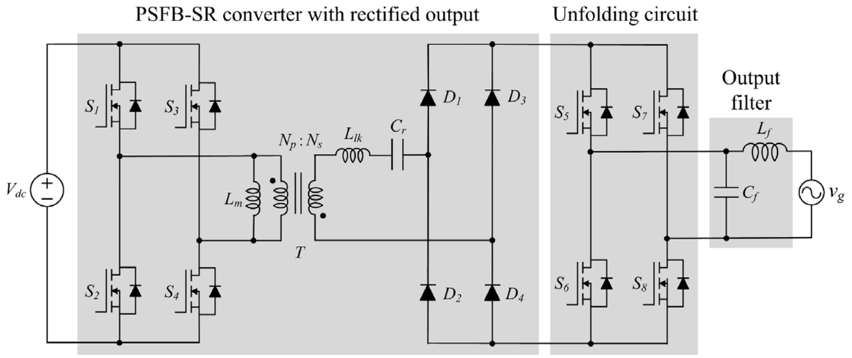

Fig. 1. Circuit diagram of the PSFB-SRI. Components and processes are described in the text.

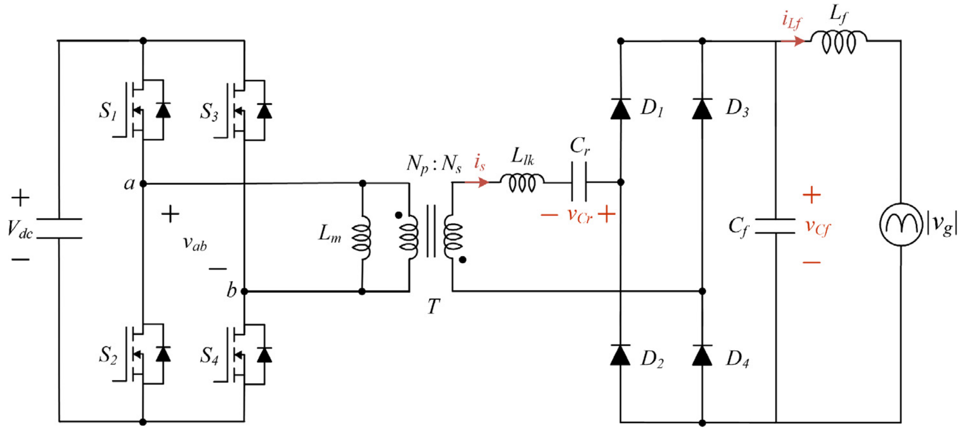

Fig. 2. Equivalent circuit of the PSFB-SRI.

state variable estimation, is designed and shown to ensure satisfactory tracking performances (Giri, El Maguiri, El Fadil, & Chaoui, 2011; Giri, Liu, & El Fadil, 2009). However, when the PSFB-SR topology is used in grid-connected dc–ac inverters, its nonlinear dynamics varies widely depending on the operating points. Furthermore, the PSFB-SRI suffers from time-varying grid voltage disturbance when it is attached to a utility grid. These aspects degrade the tracking accuracy of developed controllers, so the use of the PSFB-SRI is not currently practical despite its numerous merits.

In grid-connected applications, a scheme that combines a feed-forward controller plus feedback controller has been widely applied to control the output current of the conventional inverters. The feed-forward controller helps the inverters to generate the desired output current by alleviating the effects of disturbances, and reduces the burden of the feedback controller (Gao, Chen, Zhang, & Qian, 2014; Kim, Ji, Kim, Jung, & Won, 2013; Thang, Thao, Jang, & Park, 2014). However, the PSFB-SRI has highly nonlinear dynamics, so it is very difficult to derive the feed-forward controller for the PSFB-SRI.

The fundamental operating principle of an iterative learning controller (ILC) is to observe periodic output signals for one period and then using information derived from the observation to generate the control output for the next period. By applying an iterative learning process, the ILC can learn accurate ideal control input and achieve outstanding error-cancellation of periodic signals. Therefore, the ILC is used in several industrial applications, including: continuous casting of metals (Tsao & Bentsman, 1996; You, Kim, Lee, Lee, & Lee, 2011), optical disk drives (Moon, Lee, & Chung, 1998), manufacturing applications (Hladowski et al., 2010; Lim, Hoelzle, & Barton, 2017; Wang, Freeman, & Rogers, 2016), galvanometer scanner (Yoo, Ito, & Schitter, 2016), motors (Chi, Hou, Jin, & Huang, 2017; Inazuma, Utsugi, Ohishi, & Haga, 2013), active flow controllers (Cai, Chen, Angland, & Zhang, 2014), boost converters (Escobar, Leyva-Ramos, Martinez, & Valdez, 2005), voltage source inverters (Chen, Lai, Tan, & Tse, 2008; Yang et al., 2015; Zhang, Huang, Yao, & Lu, 2014), flyback inverters (Kim, Lee, Lai, & Kim, 2017; Lee, Cha, Kwon, & Kim, 2016), Cuk inverters (Han, Lai, & Kim, 2018; Han, Lee, & Kim, 2018), and aircraft power systems (Liu, Zanchetta, Degano, & Lavopa, 2012; Zanchetta, Degano, Liu, & Mattavelli, 2013).

In this paper, we propose the use of ILC supplemented with conventional proportional feedback controller for highly nonlinear grid-connected PSFB-SRC. Conventional proportional controller is used to improve the output current tracking performance. ILC with current learning term, which works as feed-forward controller, can guarantee the global tracking error convergence and achieve the desirable steady-state response. It is also computationally simple and easy to implement in practical applications. First-harmonic approximation of the PSFB-SRI model has been conducted and the resulting nonlinear large-signal model was used to construct the developed ILC. A detailed design guideline of the control parameters is provided. Performance and robustness of the proposed control scheme were validated by numerical simulations, and its feasibility was demonstrated in experiments using a 500-W prototype.

This paper is organized as follows. Section 2 presents the first-harmonic approximation of the PSFB-SRI model, and formulates the problem. Section 3 presents the proposed ILC scheme, and derives the convergence of output error. Section 4 describes simulation and experimental results. Section 5 provides conclusions.

2. Preliminaries and problem formulation

A key feature that distinguishes the PSFB-SRI from conventional inverters is that it has highly nonlinear dynamics. Meanwhile, it suffers from grid disturbance when it operates in grid-connected environment.