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# Design and real-time implementation of perturbation observer based sliding-mode control for VSC-HVDC systems

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ABSTRACT

This paper develops a perturbation observer based sliding-mode control (POSMC) scheme for voltage source converter based high voltage direct current (VSC-HVDC) systems. The combinatorial effect of nonlinearities, parameter uncertainties, unmodelled dynamics and time-varying external disturbances is aggregated into a perturbation, which is estimated online by a sliding-mode state and perturbation observer. POSMC does not require an accurate system model and only one state measurement is needed. Moreover, a significant robustness can be provided through the real-time compensation of the perturbation. Four case studies are carried out on the VSC-HVDC system, such as active and reactive power tracking, AC bus fault, system parameter uncertainties, and weak AC grid connection. Simulation results verify its advantages over vector control and feedback linearization sliding-mode control. Then a hardware-in-the-loop (HIL) test is undertaken to validate the implementation feasibility of the proposed approach.



## 1. Introduction

Voltage source converter based high voltage direct current (VSC-HVDC) systems using insulated gate bipolar transistor (IGBT) technology have attracted increasing attentions due to the interconnection between the mainland and offshore wind farms, power flow regulation in alternating current (AC) power systems, long distance transmission (Flourentzou, Agelidis, and Demetriades, 2009), and introduction of the supergrid, which is a large-scale power grid interconnected between national power grids (Hertema and Ghandhari, 2010). The main feature of the VSC-HVDC system is that no external voltage source is needed for communication, while active and reactive power at each AC grid can be independently controlled (Zhang, Harnefors, and Nee, 2011b).

Traditionally, control of the VSC-HVDC system utilizes a nested-loop *d*–*q* vector control (VC) approach based on linear proportional-integral (PI) methods (Haileselassie, Molinas, and Undeland, 2008), whose control performance may be degraded with the change of operation conditions as its control parameters are tuned from one-point linearization model (Li, Haskew, and Xu, 2010). As VSC-HVDC systems are highly nonlinear resulting from converters and also operate in power systems with modelling uncertainties, many advanced control approaches are developed to provide a consistent control performance under various operation conditions, such as feedback linearization control (FLC) (Ruan, Li, Peng, Sun, and Lie, 2007), which fully compensated the nonlinearities with the requirement of an accurate system model. Linear matrix inequality (LMI)-based robust control was developed in Durrant, Werner, and Abbott (2004) to maximize the size of the uncertainty region within which closed loop stability is maintained. In addition, adaptive backstepping control was designed to estimate the uncertain parameters by Ruan, Li, Jiao, Sun, and Lie (2007). In Zhang, Harnefors, and Nee (2011a), power-synchronization control was employed to greatly increase the short-circuit capacity to the AC system. However, the aforementioned methods may not be adequate to simultaneously handle perturbations such as modelling uncertainties and time-varying external disturbances.

Based on the variable structure control strategy, sliding-mode control (SMC) is an effective and high-frequency switching control for nonlinear systems with modelling uncertainties and time-varying external disturbances. The main idea of SMC is to maintain the system sliding on a surface in the state space via an appropriate switching logic, it features the simple implementation, disturbance rejection, fast response and strong robustness (Lordelo and Fazzolari, 2014). While the malignant effect of chattering

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phenomenon can be reduced by predictive variable structure (Huo, 2008) and self-tuning sliding mode (Zong, Zhao, and Zhang, 2010), SMC has been applied on electrical vehicles (Gokasan, Bogosyan, and Goering, 2006), power converters (Kessal and Rahmani, 2014), induction machines (Lascu, Boldea, and Blaabjerg, 2004), wind turbines (Beltran, Ahmed-Ali, and Benbouzid, 2008), etc. Moreover, a feedback linearization sliding-mode control (FLSMC) has been developed for the VSC-HVDC system to offer invariant stability to modelling uncertainties by Moharana and Dash (2010). Basically, SMC assumes perturbations to be bounded and the prior knowledge of these upper bounds is required. However, it may be difficult or sometimes impossible to obtain these upper bounds, thus the supreme upper bound is chosen to cover the whole range of perturbations. As a consequence, SMC based on this knowledge becomes over-conservative which may cause a poor tracking performance and undesirable control oscillations (Edwards and Spurgeon, 1998).

During the past decades, several elegant approaches based on observers have been proposed to estimate perturbations, including the unknown input observer (UIO) (Johnson, 1971), the disturbance observer (DOB) (Chen, Ballance, Gawthrop, and O'Reilly, 2000), the equivalent input disturbance (EID) based estimation (She, Fang, Ohyama, Hashimoto, and Wu, 2008), enhanced decentralized PI control via advanced disturbance observer (Sun, Li, and Lee, 2015), the extended state observer (ESO) based active disturbance rejection control (ADRC) (Han, 2009), and practical multivariable control based on inverted decoupling and decentralized ADRC (Sun, Dong, Li, and Lee, 2016). Among the above listed approaches, ESO requires the least amount of system information, in fact, only the system order needs to be known (Guo and Zhao, 2011). Due to such promising features, ESO based control schemes have become more and more popular. Recently, ESO based SMC has been developed to remedy the over-conservativeness of SMC via an online perturbation estimation. It observes both system states and perturbations by defining an extended state to represent the lumped perturbation, which can be then compensated online to improve the performance of system. Related applications can be referred to mechanical systems (Kwon and Chung, 2004), missile systems (Xia, Zhu, and Fu, 2011), spherical robots (Yue, Liu, An, and Sun, 2014), and DC–DC buck power converters (Wang, Li, Yang, Wu, and Li, 2015).

This paper uses an ESO called sliding-mode state and perturbation observer (SMSPO) (Jiang, Wu, and Wen, 2002; Liu, Wu, Zhou, and Jiang, 2014) to estimate the combinatorial effect of nonlinearities, parameter uncertainties, unmodelled dynamics and time-varying external disturbances existed in VSC-HVDC systems, which is then compensated by the perturbation observer based sliding-mode control (POSMC). The motivation to use POSMC in this paper rather than SMC and our previous work (Jiang et al., 2002; Liu et al., 2014; Yang et al., 2015) can be summarized as follows:

- The robustness of POSMC to the perturbation mostly depends on the perturbation compensation while the ground of the robustness in SMC (Beltran et al., 2008; Gokasan et al., 2006; Kessal and Rahmani, 2014; Lascu et al., 2004; Moharana and Dash, 2010) is the discrete switching input. Furthermore, the upper bound of perturbation is replaced by the smaller bound of its estimation error, thus an over conservative control input is avoided and the tracking accuracy is improved.
- POSMC can provide greater robustness than that of nonlinear adaptive control (NAC) (Jiang et al., 2002; Liu et al., 2014) and perturbation observer based adaptive passive control (POAPC) (Yang, Jiang, Yao, and Wu, 2015) due to its inherent property of disturbance rejection.

Compared to VC (Li et al., 2010), POSMC can provide a consistent control performance under various operation condition of the VSC-HVDC system and improve the power tracking by eliminating the power overshoot. Compared to FLSMC (Moharana and Dash, 2010), POSMC only requires the measurement of active and reactive power and DC voltage, which can provide a significant robustness and avoid an over-conservative control input as the real perturbation is estimated and compensated online. Four case studies are carried out to evaluate the control performance of POSMC through simulation, such as active and reactive power tracking, AC bus fault, system parameter uncertainties and weak AC grid connection. Compared to the author's previous work on SMSPO (Jiang et al., 2002; Liu et al., 2014), a dSPACE simulator based hardware-in-the-loop (HIL) test is undertaken to validate its implementation feasibility.

The rest of the paper is organized as follows. In Section 2, the model of the two-terminal VSC-HVDC system is presented. In Section 3, POSMC design for the VSC-HVDC system is developed and discussed. Sections 4 and 5 present the simulation and HIL results, respectively. Finally, conclusions are drawn in Section 6.

## 2. VSC-HVDC system modelling

There are two VSCs in the VSC-HVDC system shown in Fig. 1, in which the rectifier regulates the DC voltage and reactive power, while the inverter regulates the active and reactive power. Only the balanced condition is considered, e.g., the three phases have identical parameters and their voltages and currents have the same amplitude while each phase shifts 120° between themselves. The rectifier dynamics can be written at the angular frequency $\omega$ as (Ruan, Li, Jiao, et al., 2007)

$$\begin{cases} \dfrac{\mathrm{d}i_{\mathrm{d1}}}{\mathrm{d}t} = -\dfrac{R_1}{L_1}i_{\mathrm{d1}} + \omega i_{\mathrm{q1}} + u_{\mathrm{d1}} \\ \dfrac{\mathrm{d}i_{\mathrm{q1}}}{\mathrm{d}t} = -\dfrac{R_1}{L_1}i_{\mathrm{q1}} - \omega i_{\mathrm{d1}} + u_{\mathrm{q1}} \\ \dfrac{\mathrm{d}V_{\mathrm{dc1}}}{\mathrm{d}t} = \dfrac{3u_{\mathrm{sq1}}i_{\mathrm{q1}}}{2C_1V_{\mathrm{dc1}}} - \dfrac{i_{\mathrm{L}}}{C_1} \end{cases} \tag{1}$$

where the rectifier is connected with the AC grid via the equivalent resistance and inductance $R_1$ and $L_1$, respectively. $C_1$ is the DC bus capacitor, $u_{\mathrm{d1}} = \frac{u_{\mathrm{sd1}} - u_{\mathrm{rd}}}{L_1}$ and $u_{\mathrm{q1}} = \frac{u_{\mathrm{sq1}} - u_{\mathrm{rq}}}{L_1}$.

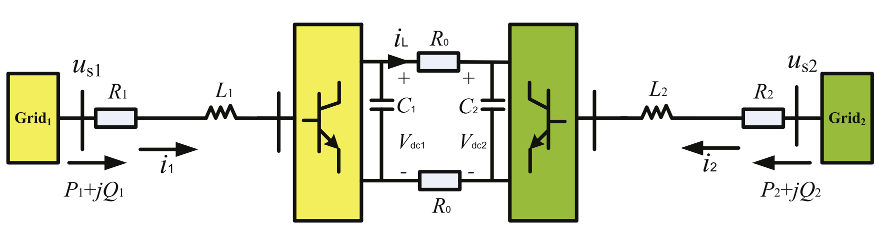


**Fig. 1.** A standard two-terminal VSC-HVDC system.