Sliding Mode Control in Power Converters and Drives: A Review

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***Abstract*—Sliding mode control (SMC) has been studied since the 1950s and widely used in practical applications due to its insensitivity to matched disturbances. The aim of this paper is to present a review of SMC describing the key developments and examining the new trends and challenges for its application to power electronic systems. The fundamental theory of SMC is briefly reviewed and the key technical problems associated with the implementation of SMC to power converters and drives, such chattering phenomenon and variable switching frequency, are discussed and analyzed. The recent developments in SMC systems, future challenges and perspectives of SMC for power converters are discussed.**

***Index Terms*—Motor drive, power electronics systems, sliding mode control.**

NOMENCLATURE

V_o	Output voltage of the dc/dc power converter
V_{in}	Input voltage of the dc/dc power converter
i_L	Inductor current of the dc/dc power converter
v_{dc}	Output voltage of grid-connected power converter
v_{abc}	AC voltage vector in abc frame
$v_{\alpha\beta}$	AC voltage vector in $\alpha\beta$ frame
v_{dq}	AC voltage vector in dq frame
i_{abc}	AC current vector in abc frame
$i_{\alpha\beta}$	AC current vector in $\alpha\beta$ frame
i_{dq}	AC current vector in dq synchronous frame
i_{dq}	AC current vector in dq synchronous frame
p, q	Active power and reactive power
C	DC-link capacitor
L	Line inductor
R_L	Load resistance
ω	Rotor speed
T	Electromagnetic torque
Ψ	Rotor flux

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I. INTRODUCTION

SLIDING mode control (SMC) is a special kind of nonlinear control which has proven to be an effective robust control strategy for incompletely modeled or nonlinear systems since its first appearance in the 1950s [1]–[4]. One of the most distinguished properties of SMC is that it utilizes a discontinuous control action which switches between two distinctively different system structures such that a new type of system motion, called sliding mode, exists in a specified manifold. This peculiar characteristic of the motion in the manifold provides insensitivity to the matched disturbances. In order to deal with the unmatched uncertainties, SMC with other approaches such as adaptive approach [5], LMI-based approach [6] and observer based approach [7], etc., have been proposed in many works [8], [9].

SMC has been applied primarily to the control of variable structure systems, its analysis and design are well presented in books, survey and tutorial papers [10]–[17], both from a theoretical and implementation perspective. In general, SMC suffers from the so-called chattering phenomena, which is undesirable because it often causes control inaccuracy, high heat loss in electric circuitry, and high wear of moving mechanical parts [18]–[20]. In addition, the chattering action may excite the unmodeled high-order dynamics, which could damage actuators, systems and even leads to unforeseen instability. The chattering in SMC systems is usually caused by

- Utilization of digital controllers with the finite sampling rate, which causes the so-called discretization chattering. Theoretically, the ideal sliding mode implies infinite switching frequency. Since the conventional SMC action is constant within a sampling interval, the switching frequency can not exceed that of half the sampling frequency, which leads to chattering.
- The unmodeled dynamics with small time constants, which are often neglected in the ideal model.

Whatever the case may be, a high switching frequency is not feasible or undesirable for practical power electronics applications due to limitations of switching devices, such as losses, time delay, response time constant, the presence of dead zone, hysteresis and saturation of device switching frequency [21].

Despite the chattering phenomena, the inherent switching nature of SMC is quite suitable and even advantageous for power converters due to its switched operation. Therefore, SMC is an interesting solution to deal with power electronics systems, such as switching dc/dc power converters, grid-connected power converters, and motor drives.

During the last few years, power electronics has undergone an intense technological evolution through the advancements of the power semiconductor industry. For example, the new generation of semiconductor switches operates with faster switching frequency and handles higher powers than the previous one. The widely used real-time computer controllers make the implementation of advanced and complex control algorithms a reality. These factors together have led to the development of cost-effective and grid-friendly converters, which play the fundamental roles in applications such as renewable energy sources and their integration into the electrical grid, motor drives, etc [22]–[25].

This paper is focused on the application of SMC for power converters and drives. The basic SMC theory is revisited and the particular problems and solutions, when applied to power electronics systems, are discussed and analyzed. Methods for solving major challenges of conventional SMC such as chattering phenomenon and variable switching frequency are addressed, and new trends and challenges for its application to power electronic systems are examined.

This paper is organized as follows: Section II briefs the fundamental theory and methodologies of SMC. The use of SMC for different types of power electronics systems are presented in Sections III to V. Future challenges to adopt SMC as an industry solution to power converters are addressed in Section VI. Finally, Section VII concludes the paper.

II. SMC Fundamental Theory and Methodologies

SMC has been recognized as an efficient tool to design robust controllers for complex high order nonlinear dynamic plants operating under various uncertainty conditions since its first appearance in the 1950s. The major advantage of the sliding mode is the low sensitivity to plant parameter variations and external disturbances which relaxes the necessity of exact modeling. SMC enables the decoupling of the overall system motion into independent partial components of lower dimension, which reduces the complexity of feedback design. SMC has been developed as a new control design method for a wide spectrum of systems including nonlinear, time-varying, discrete, large-scale, infinite-dimensional, stochastic, and distributed systems [26]. Also, in the past two decades, SMC has successfully been applied to a wide variety of practical systems such as robot manipulators, aircrafts, underwater vehicles, spacecrafts, flexible space structures, power electronics, control of electric drives, doubly fed induction generator, robotics, and automotive engines [10], [27]–[29].

In this section, the basic notion of SMC, the controller design principle and their distinguishing features are presented.

A. Fundamental Theory of SMC

Let us consider the following nonlinear system:

$$\dot{x}(t) = f(x,t) + g(x,t)u(t), \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the state variable vector, $u(t) \in \mathbb{R}^m$ is the control input, $f(\cdot,\cdot)$ and $g(\cdot,\cdot)$ are continuous functions in x and t vector fields [10], [30]. Note that the n is the dimension of the state variable vector $x(t)$, and the m is the dimension of the control input vector $u(t)$.

The sliding mode controller

$$u(t) = \begin{bmatrix} u_1(t) & u_2(t) & \cdots & u_m(t) \end{bmatrix}^{\mathrm{T}}, \tag{2}$$

is designed as

$$u_i(t) = \begin{cases} u_i^+(t), & \text{if } s_i(x) > 0, \\ u_i^-(t), & \text{if } s_i(x) < 0, \end{cases} \quad i = 1,2,\ldots,m, \tag{3}$$

where $u_i^+(t) \neq u_i^-(t)$ and $s(x) \in \mathbb{R}^m$ is the switching vector function $s(x) = [s_1(x)\ s_2(x)\ \cdots\ s_m(x)]^{\mathrm{T}}$. It undergoes discontinuities on the surface $s(x) = 0$.

Note that SMC law (3) is designed to ensure that the sliding surface ($s(x) = \mathbf{0}$) is reached and then motion on the sliding surface is maintained. This means that the so-called 'reachability condition' should be satisfied by manipulating the control law $u(t)$. The sufficient condition for the system (1) to satisfy the reachability condition is expressed as

$$s(x)\dot{s}(x) < 0. \tag{4}$$

Condition (4) guarantees that the trajectory of the system states always points towards the sliding surface. A more strict reachability condition called 'η-condition' is given as follows

$$s(x)\dot{s}(x) \leq -\eta|s(x,t)|, \tag{5}$$

where η is a positive scalar. Condition (5) ensures that the sliding surface is reached in finite time.

B. SMC Design Methods

Several SMC design methods have been proposed in literature which mainly consist of two steps [10], [30]:

Step 1: Design a sliding manifold $s(x)$ which provides desired performance in the sliding mode, such as stability, disturbance rejection capability and tracking;

Step 2: Design a discontinuous feedback control $u(t)$ which will force the system states to reach the sliding manifold in finite time, thus the desired performance is attained and maintained.

For ease of implementation, the sliding variable $s_i(x)$, $i = 1,2,\ldots,m$ is chosen as a linear combination of the state variables, expressed as

$$s_i(x) = \sum_{j=1}^{n} \alpha_{ji} x_j(t), \tag{6}$$

where α_{ji} denotes the sliding coefficients and $x_j(t) \in x(t)$. The main objective of the sliding mode controller is to drive the system state trajectories onto the specified sliding surface in a finite time and maintained there for all subsequent time. Typical SMC strategies will be introduced in the following.

1) Equivalent control-based design: For the system (1), assuming that the term $\frac{\partial s}{\partial x}g(x,t)$ is non-singular, the control law $u(t)$ is designed as follows,

$$u(t) = u_{\text{eq}}(t) + u_{\text{N}}(t), \tag{7}$$

where $u_{\text{eq}}(t)$ represents a continuous component and $u_N(t)$ represents a discontinuous component.

The equivalent control $u_{\text{eq}}(t)$ is derived from the so-called *equivalent control method*, i.e., in the case when $s(x) = \dot{s}(x) = 0$. Thus, $u_{\text{eq}}(t)$ is calculated as

$$u_{\text{eq}}(t) = -\left(\frac{\partial s}{\partial x}g(x,t)\right)^{-1}\frac{\partial s}{\partial x}f(x,t). \tag{8}$$

Substituting the above equivalent control (8) into the original system (1), it follows that the motion of sliding mode is determined by

$$\dot{x}(t) = \left[I_n - g\left(\frac{\partial s}{\partial x}g(x,t)\right)^{-1}\frac{\partial s}{\partial x}\right]f(x,t). \tag{9}$$

where (9) is considered as the equation of the sliding mode in the manifold $s(x) = 0$.

The high frequency switching action $u_N(t)$ is designed as

$$u_N(t) = -\beta\left(\frac{\partial s}{\partial x}g(x,t)\right)^{-1}\text{sign}(s(x)),\ \ \beta > 0, \tag{10}$$

such that the derivative of the Lyapunov function $V = \frac{1}{2}s(x)^{\text{T}}s(x)$ is negative, that is

$$\begin{aligned}\dot{V} &= s^{\text{T}}(x)\dot{s}(x)\\ &= s^{\text{T}}(x)\frac{\partial s(x)}{\partial x}g(x,t)u_N(t) < -\beta\|s(x)\|.\end{aligned} \tag{11}$$

Remark 1: The physical meaning of the equivalent control can be interpreted as the low-frequency component of the discontinuous control law $u(t)$, because the high-frequency $u_N(t)$ can be filtered out by a low pass filter of the system

$$\tau\dot{z} + z = u(t), \quad \tau \ll 1, \tag{12}$$

which means $z \simeq u_{\text{eq}}$.

2) Reaching law approach: The reaching law specifies the dynamics of a switching function, which can be described by the following differential equation:

$$\dot{s}(x) = -\Upsilon\text{sign}(s(x)) - K\mathrm{g}(s(x)), \tag{13}$$

where

$$\text{sign}(s(x)) = \begin{bmatrix}\text{sign}(s_1(x))\\ \text{sign}(s_2(x))\\ \vdots\\ \text{sign}(s_m(x))\end{bmatrix},$$

$$\mathrm{g}(s(x)) = \begin{bmatrix}\mathrm{g}_1(s_1(x))\\ \mathrm{g}_2(s_2(x))\\ \vdots\\ \mathrm{g}_m(s_m(x))\end{bmatrix},$$

and $\Upsilon = \text{diag}\{\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_m\}$, $\varepsilon_i > 0$, $K = \text{diag}\{k_1, k_2, \ldots, k_m\}$, $k_i > 0$, $\mathrm{g}_i(0) = 0$, $s_i(x)\mathrm{g}_i(s_i(x)) > 0$, $i = 1, \ldots, m$.

Equation (13) is only a general form of reaching law. In fact, there are many reaching laws and some special cases are

1) The constant rate reaching law:

$$\dot{s}(x) = -\Upsilon\text{sign}(s(x)),$$

2) The constant plus proportional rate reaching law:

$$\dot{s}(x) = -\Upsilon\text{sign}(s(x)) - Ks(t),$$

3) The power rate reaching law:

$$\dot{s}_i(x) = -\varepsilon_i|s_i(x)|^{\alpha}\text{sign}(s_i(x)), \quad 0 < \alpha < 1.$$

The reaching law approach not only guarantees the reaching condition but also specifies the dynamic characteristics of the motion during the reaching phase.

C. Chattering Phenomenon

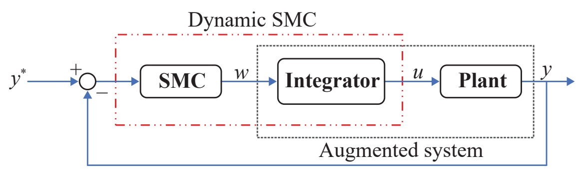
Chattering problem is one of the main obstacles for applying SMC to real applications. It is caused by unmodeled dynamics or discrete time implementation. Chattering leads to undesirable results, such as low control accuracy, high heat loss in electric circuitry, and high wear of moving mechanical parts [31]. In addition, it may excite the unmodeled high-order dynamics, which probably leads to unforeseen instability. Therefore, various methods have been proposed in literature to reduce or soften the chattering action [32]–[36]. Among others, the main approaches to avoid or limit the chattering problems are shown in Table I. It should be noted that in addition to these methods mentioned in Table I, fractional-order SMC [37] and disturbance observer based SMC approaches [7] are also common and typical approaches to soften the chattering problem.

III. SMC Strategies of DC/DC Power Converters

SMC is naturally well suited for the control of variable structure systems. Since power converters inherently include switching devices, they belong to variable structure systems. Therefore, it is straightforward to apply SMC that yields a discontinuous control law [10]. Moreover, given that power converters are usually modeled using the state space averaging method, SMC forms an efficient analysis and design tool for the control of switched mode power converters because it offers excellent large-signal handling capability.

Conventional linear control is small signal based. It only allows one to optimally operate the converters for a specific range of operating conditions and often fails to achieve satisfactory performance under large parameter/load variations, i.e., large-signal operating condition. SMC as a kind of nonlinear control method. It is suitable for controlling the power converters, which is able to achieve better regulation and dynamical performance for a wider range of operating conditions. The main reason is that there's no need to have a linear model of the power converter for nonlinear controller design. However, the main obstacle associated with the application of SMC is its variable frequency nature, which makes the design of output filter difficult. Nonetheless, if this problem is properly handled, SMC is a powerful control design method for power converters and has a huge potential

TABLE I
MAIN APPROACHES TO ALLEVIATE OR LIMIT THE CHATTERING PROBLEMS

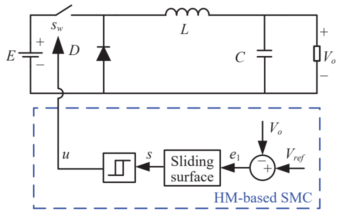
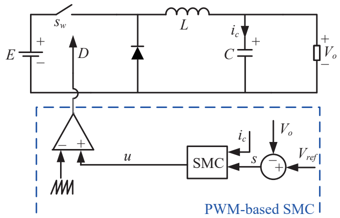
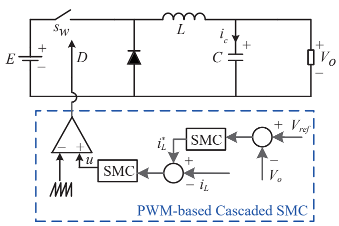
Approaches	Operation principles
Boundary layer approach	To insert a boundary layer near the sliding surface so that a continuous control action replaces the discontinuous one when the system is inside the boundary layer [38]. For this purpose, the discontinuous component of the controller: $$u_N(t) = -K_s \operatorname{sign}(s(x)),$$ is often replaced by the saturation control: $$u_N(t) \approx -K_s \frac{s(x)}{\|s(x)\| + \delta},$$ for some, preferably small, $\delta > 0$. The boundary layer approach has been utilized extensively to practical applications. However, this method has some disadvantages such as: • It may give a chattering-free system but a finite steady-state error must exist; • The boundary layer thickness has the trade-off between control performance of SMC and chattering mitigation; • Within the boundary layer, the characteristics of robustness and the accuracy of the system are no longer assured.
Reaching law approach	Since the amplitude of chattering depends on the magnitude of control, the intuitive way of chattering reduction is to decrease the amplitude of the discontinuous control [39]. This technique affects the robustness property of the controller and degrades the transient response of the system. Therefore, exists a trade-off between the chattering reduction and the system performance. A compromised approach is to decrease the amplitude of the discontinuous control, $u_N(t)$, when the system state trajectories are near to sliding surface (to reduce the chattering), and to increase the amplitude when the system states are far from the sliding surface.
Dynamic SMC approach	The main idea of the dynamic SMC approach is to insert an integrator (or any other strictly proper low-pass filter) between the SMC and the controlled plant [40]. The concept is illustrated here:  The time derivative of the control input, ω, is treated as the new control input for the augmented system. Since the low-pass integrator filters out the high frequency chattering in ω, the control input to the real plant, u, becomes continuous which offers a possibility to reduce chattering. Such a method can eliminate chattering and ensure zero steady-state error, however, it should be noted that the system order is increased by one and the transient responses may be degraded [41].
SOSMC approach	Second order sliding mode control (SOSMC) approach is one of the most popular methods to alleviate the chattering problems, which not only effectively eliminates the disadvantages of the conventional SMC, but also maintains its all major attributes such as strong robustness and finite time convergence. The common SOSMC algorithms include twisting algorithm, super-twisting algorithm, drift algorithm and prescribed convergence law algorithm, etc. All these algorithms guarantee that system state can converge $s = \dot{s}$ in finite time [42]–[45]. Among these second order sliding mode control algorithms, super-twisting algorithm viewed as nonlinear proportional-integral control is very effective to deal with the system in presence of strong nonlinearity effects [46]. The super-twisting algorithm can be expressed as, $$u_{sta}(t) = u_{sta1}(t) + u_{sta2}(t),$$ $$u_{sta1}(t) = -\lambda_1 \operatorname{sign}(s(x)), \quad u_{sta2}(t) = -\lambda_2 \lvert s(x) \rvert^{0.5} \operatorname{sign}(s(x)),$$ where λ_1 and λ_2 are positive design parameters.
Intelligent SMC approach	The main idea of the intelligent SMC approach is integration of SMC with intelligent control technologies, such as neural networks (NNs), fuzzy logic technologies, etc., to make it smarter [47]–[49]. Depending on the technology different goals can be defined as follows. • NNs allows one to approximate smooth nonlinear functions to arbitrary accuracy. Therefore, they can be used to approximate and compensate external disturbances and model uncertainties to soften the chattering. On the other hand, NNs in SMC can be also aimed to estimate the switching control term in which the discontinuous control signal is converted to a continuous control signal providing an efficient method to reduce the chattering. • The purpose of adding fuzzy logic systems to SMC is similar to NNs. It allows one to approximate smooth nonlinear functions to arbitrary accuracy. Then it is used to estimate the external disturbance and modeling uncertainties to alleviate chattering. • Evolutionary computation is an alternative to seek optimal control parameters. Thus it can be used to alleviate chattering.

in industrial applications [21].

Many sliding-based controllers have been proposed for dc/dc converters, such as SMC based on Hysteresis-Modulation (HM) technique or fixed-frequency SMC [52]–[54]. As it is well known, the direct implementation of SMC will result in some high and uncontrolled switching frequency which makes them unsuitable for industrial applications. HM-based SMC is adopted to limit the operating frequency via tuning the hysteresis parameter. It should be noted that the operating frequency is only limited but it is still variable [21].

Generally, there are three approaches to make the switching frequency constant. The first approach is to incorporate a constant ramp or timing function directly into the controller [55]. The second approach is to apply the adaptive hysteresis concept, with a hysteresis level which can be varied with both input and output voltages to force the switching frequency to remain a constant under all load conditions [50]. The third

TABLE II
SMC STRATEGIES FOR BUCK CONVERTER

Techniques	Structures	Sliding surfaces	Control laws
HM-Based SMC [50]		$s = K_{\rm p}(V_{\rm ref} - V_{\rm o}) + i_o - \int \frac{uV_{\rm i} - V_{\rm o}}{L} dt$, where K_p is a positive constant and i_o is the output current.	$u = \begin{cases} 1, & \text{if } s > \kappa, \\ 0, & \text{if } s < -\kappa, \\ \text{unchanged}, & \text{otherwise.} \end{cases}$
PWM-Based Direct Voltage SMC [21]		$s = \alpha_1(V_{ref} - V_0) + \alpha_2 \frac{d(V_{ref} - V_0)}{dt} + \alpha_3 \int (V_{ref} - V_0)dt$, where α_1, α_2 and α_3 are the sliding coefficients.	$u = u_{eq} + K_{p3}\text{sign}(s)$, $u_{eq} = K_{p1} i_C + K_{p2}(V_{ref} - V_0) + V_0$, where $K_{p2} = \frac{\alpha_3}{\alpha_2} LC$, $K_{p3} > 0$ and $K_{p1} = L\left(\frac{\alpha_1}{\alpha_2} - \frac{1}{R_L C}\right)$.
PWM-Based Cascaded SMC [51]		External loop $s_1 = V_{ref}^* - V_o$ and internal loop $s_2 = i_L^* - i_L$.	$i_L^* = \lambda_1 \lvert s_1 \rvert^{\frac{1}{2}} \text{sign}(s_1) + \alpha_1 \int_{t_0}^{t} \text{sign}(s_1) ds$, $u = \frac{L}{E}\left(u_2(s_2) + \frac{V_o}{L} + \frac{R_L}{L} i_L\right)$, $u_2(s_2) = \mu_2 \lvert \sigma(s_2) \rvert^{\frac{1}{2}} \text{sign}(s_2) + \alpha_2 \int_{t_0}^{t} \text{sign}(s_2) ds$, where μ_1, μ_2, α_1 and α_2 are positive constants.

approach is to achieve constant switching frequency by employing PWM technique. The PWM-based SMC can be obtained by translating the equivalent control $u_{\rm eq}$ to the duty ratio of the PWM, d. The equivalent control signal $u_{\rm eq}$ is calculated by setting the derivative of the sliding variable to zero, i.e, $\dot{s} = 0$. The control signal u is compared to the PWM carrier to generate a discrete gate pulse signal.

Mazumder *et al.* proposed a first fixed-frequency PWM-based integral variable structure sliding mode controller for parallel buck converters [53]. This technique was subsequently extended for control of the voltage regulator module application in [56]. Later, a unified fixed-frequency PWM-based direct sliding mode voltage control design was proposed for the buck, boost and buck-boost converters [57]. Its main disadvantage is that it lacks robustness against system parameters, i.e., load resistance and capacitors. Pointed out by [12] that direct sliding mode voltage control for boost and buck/boost converters may result in the instability of the system. Cascade control structure which consists of an inner current loop and outer voltage loop is introduced to solve this problem. This control method increases the overall system's stability (phase) margin, and hence simplifies the design of the outer voltage loop. It can be concluded from [58] that sliding mode current controller may be a good alternative over conventional current-mode controllers for fast-response boost-converter applications but at a higher implementation cost and circuit complexity.

As an illustrative example, three SMC strategies for buck converter are presented in the discussion. The mathematical model of the typical buck converter can be expressed as,

$$\frac{dV_o}{dt} = \frac{i_L}{C} - \frac{V_o}{R_L C},$$
$$\frac{di_L}{dt} = u\frac{V_{in}}{L} - \frac{V_o}{L}, \tag{14}$$

where L, C and R_L represent inductor, storage capacitor and load resistance, respectively; i_L, V_{in} and V_o are inductor current, input voltage and output voltage, respectively.

However, these strategies are generally applicable to any dc/dc converter types. Basic structures of typical HM-based SMC, fixed-frequency PWM based SMC and cascade control structure for a dc/dc converter system are shown in Table II.

A. SMC Based on HM Technique

The schematic diagram of the buck converter with an HM-based SMC is shown in Table II. The sliding surface s is defined as

$$s = \frac{1}{R_L C}\left(V_{ref} - V_0\right) + \frac{d}{dt}\left(V_{ref} - V_0\right) = \frac{1}{R_L C}\left(V_{ref} - V_0\right) - \frac{i_c}{C}, \tag{15}$$

where C and R_L are the capacitance, and instantaneous load resistance, respectively. V_{ref} and V_0 are the desired and capacitor output voltage, respectively.

To drive the trajectories onto the sliding surface $s = 0$, the control law u can be designed as:

$$u = \begin{cases} 1, & \text{if } s > 0, \\ 0, & \text{if } s < 0. \end{cases} \tag{16}$$

where $u = 1$ corresponds to the conducting state of the switching element s_ω while $u = 0$ corresponds to nonconducting state of the switching element s_ω.

Remark 2: It is worth noting that, in the ideal sliding mode, the state trajectories are directed towards the sliding surface at an infinite switching frequency. However, practical applications limit the switching frequency to reduce the power losses in the converter. A hysteresis band with the boundary conditions $s = \kappa$ and $s = -\kappa$ is introduced to deal with this problem. The control law in (16) is redefined as

$$u = \begin{cases} 1, & \text{if} \quad s > \kappa, \\ 0, & \text{if} \quad s < -\kappa, \end{cases} \tag{17}$$

where κ is an arbitrarily small value.

The introduction of hysteresis band only solves the problem of high switching losses, however, variable switching frequency still exists. PWM techniques are employed to achieve constant switching frequency SMC.

B. Fixed-frequency PWM Based SMC

The schematic diagram of the buck converter with a fixed-frequency PWM-based SMC is presented in Table II. The main idea is to use a pulse-width modulator that employs an equivalent control signal to be compared with the fixed-frequency ramp in the modulator. The sliding surface s is defined as,

$$s = \alpha_1\left(V_{ref} - V_0\right) + \alpha_2 \frac{d\left(V_{ref} - V_0\right)}{dt} + \alpha_3 \int \left(V_{ref} - V_0\right) dt, \tag{18}$$

where the positive constants α_1, α_2 and α_3 are the sliding coefficients [21]. Then the control law u can be designed as:

$$u = u_{eq} + K_{p3}\text{sign}(s), \tag{19}$$

where $u_{eq} = K_{p1} i_C + K_{p2}\left(V_{ref} - V_0\right) + V_0$ is the equivalent control calculated from $\dot{s} = 0$, $K_{p1} = L\left(\frac{\alpha_1}{\alpha_2} - \frac{1}{R_L C}\right)$, $K_{p2} = \frac{\alpha_3}{\alpha_2} LC$ and $K_{p3} > 0$.

This approach solves the problem of a resulting variable switching frequency but may lead to system instability.

C. Cascade Control Structure

The schematic diagram of the buck converter with a cascade control structure based SMC is presented in Table II. A cascade-control comprises two control loops. The voltage regulation loop is the external loop which provides the current reference for the inner loop [51]. The sliding surface is defined as

$$s_1 = V_{ref} - V_o, \tag{20}$$

and the control law i_L^* in the external loop can be designed as

$$i_L^* = \lambda_1 |s_1|^{\frac{1}{2}} \text{sign}(s_1) + \alpha_1 \int_{t_0}^{t} \text{sign}(s_1) ds, \tag{21}$$

where λ_1 and α_1 are positive constants.

The inner loop is focused on the current tracking. In this case, the sliding surface is defined as

$$s_2 = i_L^* - i_L, \tag{22}$$

and the control law u in the internal loop can be designed as

$$u = \frac{L}{E}\left[\mu_2(s_2) + \frac{V_o}{L} + \frac{R_L}{L} i_L\right], \tag{23}$$

where $\mu_2(s_2) = \lambda_2 |s_2|^{\frac{1}{2}} \text{sign}(s_2) + \alpha_2 \int_{t_0}^{t} \text{sign}(s_2) ds$ with positive constants λ_2 and α_2.

This approach provides fixed switching frequency and offers more robustness compared with direct voltage SMC. The features of different SMC techniques for a dc-dc buck converter are presented in Table III.

IV. SMC for Grid-Connected Power Converters

With the advent of distributed dc power sources in the energy sector, grid-connected power converter plays a key role in industrial applications like integration of renewable energy sources such as wind power systems or photo-voltaic, energy storage systems, motor drives, battery charger in electric vehicles, etc [59]–[63]. PWM converters can operate with a high power factor or any active/reactive power combination. Typically, in the application of renewable energy sources, power converter plays an important role in transforming the renewable energy in electrical energy efficiently and economically. For electric vehicles, power converter works as an interface in the electrical propulsion system turning electrical power to mechanical power for sake of efficiently driving the electric motor. It is also known as the active front end (AFE), which is grid-connected converter that offers features as bidirectional power flow, near-sinusoidal currents, power factor and dc-link capacitor voltage regulation capability [64]. The typical AFE is the three-phase two-level grid-connected power converters and its mathematical model in dq synchronous can be described as

$$\begin{aligned} \dot{i}_{dq}(t) &= -\frac{r}{L} i_{dq}(t) - J\omega i_{dq}(t) + \frac{v_{dq}}{L} - \frac{1}{L} u_{dq} v_{dc}(t), \\ \dot{v}_{dc}(t) &= -\frac{1}{R_L C} v_{dc}(t) + \frac{1}{C} u_{dq}^T(t) i_{dq}(t), \end{aligned} \tag{24}$$

where $i_{dq}(t) = [i_d(t), i_q(t)]^T$, $v_{dq} = [v_d, v_q]^T$, $u_{dq}(t) = [u_d(t), u_q(t)]^T$, $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$.

Different generic loads can be connected to the dc-link depending on the direction of the power flow. A resistive load is connected to the dc-link as a rectifier. For grid integration of renewable energies such as wind power, a power converter (rotor side converter) is connected to the dc-link for the torque and/or speed regulation [70].

The main control objectives for AFE are to regulate the dc-link voltage V_{dc} to a certain reference V_{dc}^* for any connected load and supply a desired reactive power and draw grid currents with the lower harmonic distortion. Several control methods have been proposed for the control of power converters [71]. In general, a cascade control structure is used which consists of an external control loop and inner control loop. The external control loop is employed to regulate the dc-link voltage to some desired value. The inner control loop is designed to force the grid currents or the instantaneous active and reactive power to track their references [72], [73]. As discussed in [71], the performance of the converter system largely depends on the quality of the inner control strategy. Since grid-connected power converters are variable structure systems, sliding mode techniques are desirable to tackle their control problems. They are able to ensure stability, robustness

TABLE III
THE FEATURES OF DIFFERENT SMC TECHNIQUES FOR DC-DC BUCK CONVERTER

Control Scheme		Features
HM-Based SMC		• The order of the resultant control system is 2. • The output voltage regulation error, integral term of voltage error and output current are considered into the sliding surface, which can improve output voltage performance such as steady-state error, etc. • The computational time is short, where it adopts the first order SMC and does not use estimator. • It needs to measure load current or knows the load information, which may increase the system complexity, cost and also limit the application range. • The control parameters are easy to tune. • The hysteresis modulation technique is adopted to alleviate the problem of frequency variation caused by line and load variations via tuning the hysteresis parameter. However, the operating frequency is only limited but it is still variable, which increases the switching losses and the complexity of the filter design.
PWM-Based SMC	Single-loop control structure	• The order of the resultant control system is 1. • The sliding surface considers voltage regulation error, the rate of change of voltage error, and the integration of voltage error, which can improve output voltage performance with fast dynamical response and small voltage overshoot. • Computational time is short, where it adopts the first order SMC and only has one control loop. • It does not need to measure the current leading to simple implementation, which has wide range application. • The sliding coefficients have a great effect on the dynamic of the output voltage, and it is relatively difficult to tune. • The PWM technique is adopted to generate a constant switching frequency, which can provide comparatively better steady-state line and load regulated converters.
	Double-loop control structure	• The order of the resultant control system is 2. • It needs two sliding surfaces, where one is for the voltage regulation loop and the other is for the current tracking loop. However, only voltage regulation error is considered in both sliding surfaces. • Computational time is relatively longer, because it has two control loops and uses an estimator and both them utilize second order sliding mode controllers. • An extended state observer is used to estimate load resistance, considered as the unknown disturbance, improving the robustness of the converter. However, it also adds complexity for control strategy. On the other hand, it still needs to measure the inductor current. • It has more control parameters and thus increase the difficulty of tuning the parameters. • By employing PWM technique, the switching frequency is constant, mapping the duty cycle to the equivalent control signal. • Compared with the single loop, this control structure has a strong anti-interference ability, but needs longer response time.

and increase the dynamic response in the presence of parameter uncertainties and external disturbances. The cascade control structure, which includes outer control loop and inner control loop [74], employing SMC for AFE is shown in Fig. 1. SMC for grid-connected power converters is summarized in Tables IV and V.

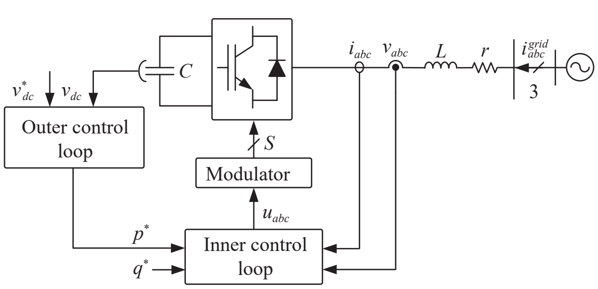


Fig. 1. Cascade control structure for grid-connected power converters.

Many research endeavors have been focused during the recent years, on control problems in PWM rectifiers. Silva [65] designed a robust sliding-mode controller, suitable for the output voltage control of voltage-sourced unity-power-factor three-phase PWM rectifiers. Through the comparison with PI controller, it shows that the robust sliding-mode controller offers faster dynamics and does not present steady-state errors. Control methods based on state-space average models, using linear regulators for the rectifier output voltage control, must change the modulation index slowly, to ensure stability, thus losing response speed. However, the PI regulator parameters are dependent on the load, system parameters, and on the operating point. Responses, with loads far from the nominal one, are not good enough, presenting rise times and damping factors depending on the load and on the rectifier operating point. Some works have treated the sliding-mode control of these PWM rectifiers just considering the slow and fast manifold approximation [75]. Therefore, they control only the input currents in sliding mode and this approach yields robust input current controllers, but non-robust output voltage controllers. Furthermore, their robustness can only be improved using complex control processes.

Pires *et al.* [76] proposed a cascade sliding mode controller for a three-phase buck-boost-type rectifier. In the inner current loop, a vector-based sliding-mode control method is used to generate ($\alpha\beta$) space-vector modulation, which forces the input line currents to track a suitable sinusoidal reference. In the outer voltage regulation loop, a PI controller is adopted to regulate the output voltage of the converter. In order to guarantee robustness against load variation, a composite control law consisting of super-twisting based SMC and an extended state observer is developed for the voltage regulation loop [66].

TABLE IV
SMC FOR GRID-CONNECTED POWER CONVERTERS: OUTER CONTROL LOOP

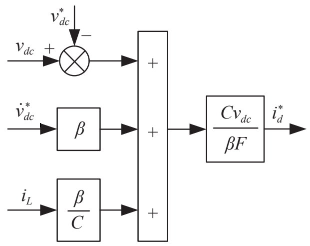
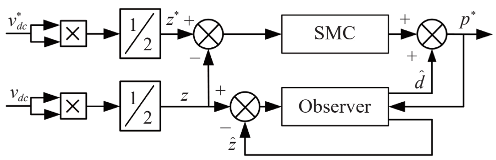
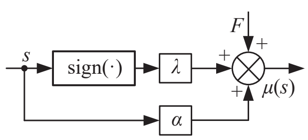
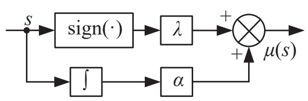
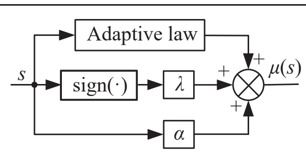
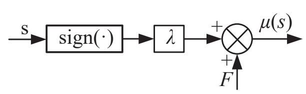
Techniques	Structures	Sliding variables	Control laws
Conventional SMC [65]		$s = e_v + \beta\dot{e}_v$, where $e_v = v_{dc} - v_{dc}^*$ and β is the positive constant.	$i_d^* = \left(e_v + \beta\dot{v}_{dc}^* + \frac{\beta}{C}i_L\right)\frac{Cv_{dc}}{\beta F}$ where F is the constant.
Second order SMC [66]		$s = z^* - z$.	$p^* = \mu_{dc}(\tilde{z}) + \hat{d}(t)$, where $\tilde{z}$ is the regulation error, $\hat{d}(t)$ is disturbance estimate and $\mu_{dc}(\tilde{z})$ is SMC with the following form: $\mu_{dc}(\tilde{z}) = -\lambda_{dc}\lvert\tilde{z}\rvert^{\frac{1}{2}}\,\mathrm{sign}(\tilde{z}) + \alpha_{dc}\int_{t_0}^{t}\mathrm{sign}(\tilde{z})d\tau$, in which λ_{dc} and α_{dc} are positive constants.

TABLE V
SMC FOR GRID-CONNECTED POWER CONVERTERS: INNER CONTROL LOOP

Technique	Structures	Sliding variables	Control laws
Conventional SMC [67]		$s_d = i_d^* - i_d$, $s_q = i_q^* - i_q$.	$\mu_d = \lambda_d\mathrm{sign}(s_d) + \alpha_d s_d + F_d$, $\mu_q = \lambda_q\mathrm{sign}(s_q) + \alpha_q s_q + F_q$. where F_d and F_q are positive constants.
Second order SMC [66]		$s_d = i_d^* - i_d$, $s_q = i_q^* - i_q$.	$\mu_d = -\lambda_d\lvert s\rvert^{\frac{1}{2}}\,\mathrm{sign}(s) + \alpha_d\int_{t_0}^{t}\mathrm{sign}(s)d\tau$, $\mu_q = -\lambda_q\lvert s\rvert^{\frac{1}{2}}\,\mathrm{sign}(s) + \alpha_q\int_{t_0}^{t}\mathrm{sign}(s)d\tau$,
Adaptive SMC [68]		$s_p = p^* - p$, $s_q = q^* - q$.	$\mu_p = \lambda_p\mathrm{sign}(s_d) + \alpha_j s_p + \theta_p$, $\mu_q = \lambda_q\mathrm{sign}(s_q) + \alpha_j s_q + \theta_q$, where θ_d and θ_q are the adaptive parameters.
Integral SMC [69]		$s_p = e_p + \lambda_p\int_0^t e_p d\tau - e_p(0)$, $s_q = e_q + \lambda_q\int_0^t e_q d\tau - e_q(0)$, where $e_p = p^* - p$ and $e_q = p^* - q$.	$\mu_p = \lambda_p\mathrm{sign}(s_p) + F_p$, $\mu_q = \lambda_q\mathrm{sign}(s_q) + F_q$, where F_p and F_q are the positive constants.

While SMC has been extensively researched in the context of standalone PWM rectifiers, pioneering work has been conducted in [77], where SMC has been applied to plurality of PWM rectifiers connected in a parallel configuration to feed a dc bus from power delivered by a ac multiphase power source. In this application, SMC has been integrated with novel space-vector modulation [78] in a three-dimensional synchronous frame to not only alleviate problems associated with circulating currents in non-isolated parallel PWM rectifiers but also achieve constant frequency of operation even while achieving high quality performance while satisfying stability bound. Subsequently, additional SMC was developed in [79].

Most of the above works need continuous measurements of ac voltages, ac currents and dc voltage. This requires a large number of both voltage and current sensors, which increases system's complexity, cost, space and reduces system reliability. Moreover, the sensors are susceptible to electrical noise, which cannot be avoided during high-power switching. Reducing the number of sensors has a significant effect upon the control system's performance. In [80], a simple control scheme was presented for the three-phase power converter without using a current sensor, where the current command can be automatically adjusted. By using the information from dc-link current sensor, a technique of reconstructing three-phase input currents was given to control three-phase voltage-source converters in [81]. Lee *et al.* [82] proposed a control strategy for three-phase power converter without using any ac input current and voltage sensors in order to achieve desired control performance of the dc output voltage regulation over a wide range. The input phase currents are reconstructed from the switching states of the ac/dc rectifier and the measured dc-link currents, and then used in feedback control. The phase angle and the magnitude of the source voltage were estimated by controlling the deviation between the rectifier current and its model current to be zero. However, they require digital sampling of the dc-link current in every switching cycle and numerical computations. The accuracy of measurement is inherently controlled by the sampling rate.

V. SMC for High Performance Motor Drives

For the control of the motor drive system, the conventional PI control has been commonly adopted because of its simplicity, strong adaptability and reliability. Nevertheless, PI control may not guarantee that the motor has high performance under parameter and load variations. Thus, a large amount of advanced control methods, such as model predictive control [70], [83], [84], adaptive control [85], [86], fuzzy control [87] and SMC [88]–[90], etc., have been proposed to improve the performance of the motor. Among these advanced control approaches, SMC can perfectly deal with the disturbances and uncertainties of the motor system causing unmodeled dynamics, friction force, and load disturbances to reach a high performance for motor control.

Fig. 2 is a typical cascade control structure employing SMC for the motor drives [91]–[93]. Note that the speed observer in the Fig. 2 is not mandatory, only for the speed sensor less control strategies. In [92], [93], the continuous fast terminal sliding mode control (CFTSMC) is adopted in the outer control loop to regulate speed of permanent magnet synchronous motor (PMSM), shown in Fig. 3. In which the CFTSMC is designed as,

$$i_q^* = m^{-1}(\chi_{eq} + \chi_b), \tag{25}$$

$$\chi_{eq} = \dot{\omega}^* + \mu_1|\dot{\varepsilon}|^{\sigma_1}\mathrm{sign}(\dot{\varepsilon}) + \mu_2|\varepsilon|^{\sigma_2}\mathrm{sign}(\varepsilon), \tag{26}$$

$$\chi_b = \int_0^t k_1 s + k_2|s|^{\sigma_3}\mathrm{sign}(s)d\gamma, \tag{27}$$

where ε is speed error, s is sliding variable, m is parameter of PMSM and μ_1, μ_2, k_1 and k_2 are the positive constants to be designed. It should be noted that the main idea of TSMC evolved out of seminal work on terminal attractors, and is evoked by the concept of terminal attractors which guarantee finite time convergence of the states. Thus, compared with traditional SMC, TSMC can guarantee that can make the closed loop system converge to equilibrium in finite time.

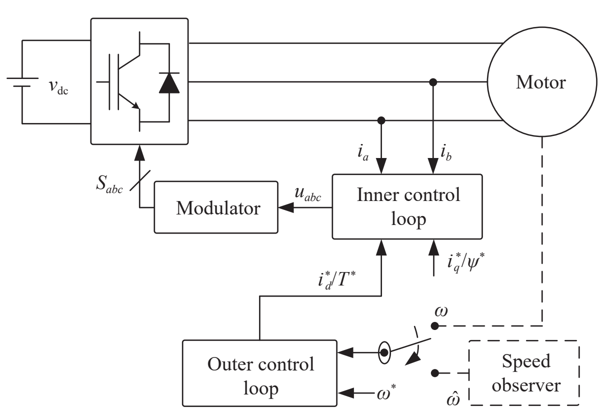


Fig. 2. The block diagram of SMC for the motor speed-regulation system.

The simulation and experimental results demonstrated that CFTSMC has superior performance than the conventional approaches. The SMC for motor drive systems is summarized in Tables VI and VII. Here it should be pointed out that the current based SMC method in the inner control loop for motor drives systems is similar to the grid-connected power converters, which can be seen in Table V. Thus there are only the torque and flux variables based SMC methods given in the Table VII.

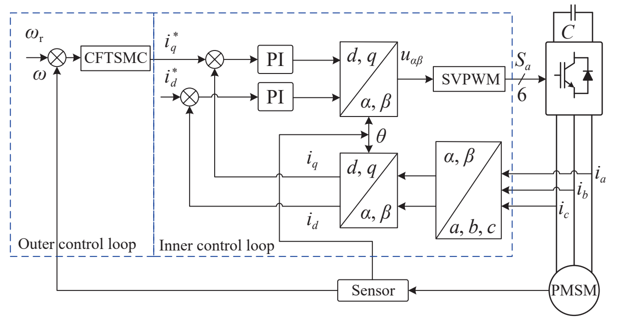


Fig. 3. The control structure for the motor speed-regulation system using terminal sliding mode control.

On the other hand, a number of sensors are used in the systems (e.g., speed/position sensors), which increases not only installation difficulty but also cost. Therefore, it is of great interest proposing speed/position sensor-less control strategies in order to reduce cost and improve system reliability [98]. Many research endeavors have been focused on sensor-less control design problems during the recent years, Kalman filter (extended Kalman filter) [99], adaptive observer [100], and sliding-mode observer [101], and so on. Although most of them are able to get accurate speed or position information, they either depend largely on the machine parameters or require a large computational burden.

With its inherent advantages, order reduction, good dynamic performance and robustness to parameter variations and disturbances, sliding mode observer has widely applied in the sensor-less motor drives. In [102], a flatness-based SOSMC combined with an angular velocity second order sliding mode observer was designed for the stepper motor. The angular displacement and the direct current are chosen as flat outputs such that other states or input variables can be presented as a function of the flat outputs and their time derivatives up to some finite number. The practical stability of the closed-loop system was obtained inherently. For the real-time implementation of the designed control law, the online parameter identification should be taken into consideration. Shtessel *et al.* [103] designed a parameter observer to estimate the load resistance and parasitic phase resistance. An adaptive interconnected observer with online parameter identification (the stator inductance and the stator resistance) was proposed in [104]. It should be noted that above works require the utilization of the current sensors. Wang *et al.* [105] proposed an adaptive filter with the sliding mode observer for position sensor-less motor drives, and the approach was verified with the experimental results. Two novel sliding mode model reference adaptive system observers were successfully applied in the sensor-less induction motor drive [106]. Compared with the classical observer, the dynamics obtained by sliding mode model reference adaptive system observers do not exhibit

TABLE VI
SMC FOR MOTOR DRIVES: OUTER CONTROL LOOP

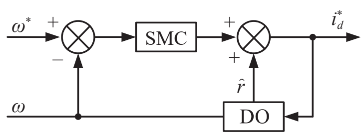
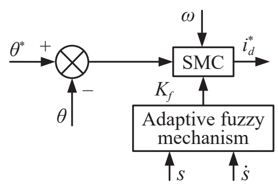
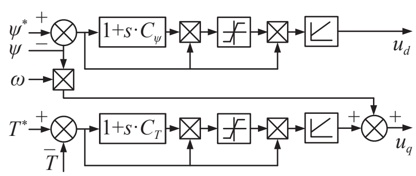
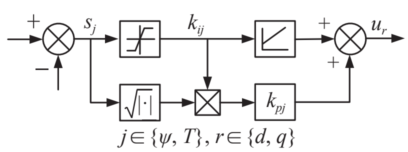
Techniques	Structures	Sliding variables	Control laws
Disturbance observer based SMC [94]		$s=\omega^*-\omega.$	$i_d^*=a^{-1}[\omega^*+c\omega+(l+k)\text{sign}(s)]$, where a and c are nominal parameter, and l and k are control parameters.
Adaptive fuzzy SMC [95]		$s=C[x-\int_0^t(A+BK)x(\tau)d\tau]$, where $x=[x_1,x_2]^T$, $x_1=\theta^*-\theta$, $x_2=\omega$, A and B are the system matrix and input matrix, respectively, C is set as a positive constant matrix, and K is a state feedback gain matrix.	$i_d^*=Ks-K_f\text{sign}(s)$, where K_f is a control parameter.

TABLE VII
SMC FOR MOTOR DRIVES: INNER CONTROL LOOP

Techniques	Structures	Sliding variables	Control laws
Conventional SMC [96]		$s_\psi=e_\psi+c_\psi\dot{e}_j$, $s_T=e_T+c_T\dot{e}_T$, where $e_\psi=\psi^*-\psi$, $e_T=T^*-T$, and c_ψ and c_T are positive constants.	$u_d=\left(k_{dp}+\frac{k_{di}}{s}\right)(e_d+\text{sign}(s_d))$, $u_q=\left(k_{qp}+\frac{k_{qi}}{s}\right)(e_q+\text{sign}(s_q))+\omega\psi$.
Second order SMC [97]		$s_\psi=\psi^*-\psi$, $s_T=T^*-T$.	$u_d=-k_{p\psi}\|s\|^{\frac{1}{2}}\text{sign}(s)+k_{i\psi}\int_{t_0}^t\text{sign}(s)d\tau$, $u_q=-k_{p\psi}\|s\|^{\frac{1}{2}}\text{sign}(s)+k_{i\psi}\int_{t_0}^t\text{sign}(s)d\tau$,

damped responses or speed dip. In [107], an adaptive sliding-mode observer was designed for sensorless speed control of an induction motor, which contains three observers. Two sliding-mode observers are designed to estimate currents and the third observer is used to estimate rotor flux which is based on the current observers. This can diminish the influence of parameters variations on the flux and speed estimation. The control structure based on adaptive sliding-mode observer for sensor-less speed control is shown in Fig. 4, where the block diagram of adaptive sliding-mode observer is presented in Fig. 5. Note that the above observers only perform well in high and medium speed since the low signal-to-noise-ratio caused by modeling uncertainty and nonlinearity [108].

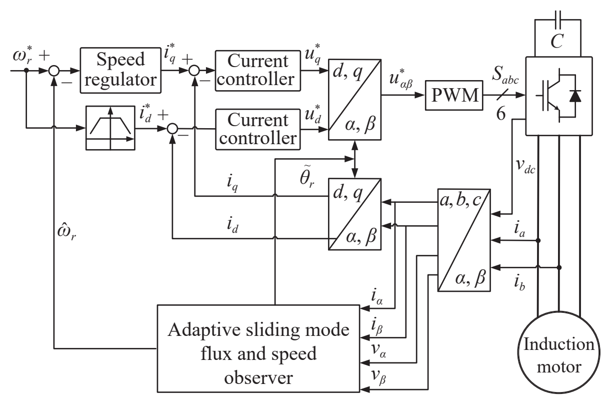


Fig. 4. Control structure for sensor-less speed control.

VI. FUTURE CHALLENGES AND PROSPECTS OF SMC FOR POWER CONVERTERS

SMC was effective solution for power converters and motor drives during the last decades. However, there are still several remaining issues that should be solved before it can be extensively used in the industry in the near future.

• Despite the advantages of simplicity and robustness, a main drawback of the pure SMC strategies is chattering which is a high-frequency oscillating occurring in the control process. In recent years, new SMC mechanisms such as higher-order sliding mode, terminal SMC and adaptive SMC have been introduced in order to alleviate the chattering problem. Although these new SMC approaches offer promising dynamical properties, theoretical proofs of finite time convergence and stability analysis are still open problems due to the introduction of non-smoothness and discontinuous terms. Future research activities in this area are definitely required.

• In commercial applications, the use of SMC for basic low-order power converters has been deemed unrealistic because of higher complexity compared to existing linear controllers. From a cost perspective, the idea of applying SMC in high-order power converters is of great value which provides

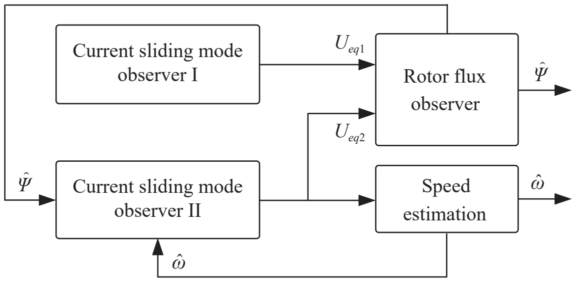


Fig. 5. The block diagram of adaptive sliding-mode observer.

desired performance over a large operating condition. However, for practical implementation of SMC to power converters, it only allows operating at limited frequency ranges while the ideal operation of SMC requires infinitely high frequency.

• Since the control strategies are implemented in digital microprocessor nowadays, the ideal sliding motion, invariability and stability cannot be guaranteed in the continuous time domain due to the discretized sampling. Thus discrete-time sliding mode control is needed, which takes control design in a more generalized sense. Future research about design discretized quasi-sliding mode control schemes for converters and drivers is still needed.

• Considering complex systems whose models have multiple variables, multiple parameters, and nonlinear couplings, it is evident that SMC techniques are inadequate to analyze and predict the behavior of such systems. Intelligent algorithms have proven to be efficient methods dealing with the intricacy and the complexity of the practical industrial systems. Furthermore, due to the fast development of powerful DSPs and field-programmable gate array, high-performance control algorithms can be easily implemented for complex industrial systems. Among various intelligent control techniques, fuzzy logic and neural networks are becoming more and more popular in the applications where the mathematical model is not accurate or the model is ill-defined. Therefore, the integration of intelligent control techniques and SMC can solve the problems met in practical implementations of SMC for complex systems. The major developments in this research area have been outlined in the earlier surveys [5], [7].

VII. CONCLUSIONS

This paper has reviewed the applications of SMC to different types of power converters, i.e., dc/dc converters and three-phase voltage source PWM converters. Several control schemes used to obtain ac/dc conversion with bidirectional power flow and regulation power factor have also been discussed. SMC is a well-known nonlinear control technique which has achieved high-performance operation in a wide application range. The distinctive feature of SMC is its robustness against parametric uncertainties and external perturbations. The main problem associated with the application of SMC to power converters is its variable switching frequency nature, which causes excessive switching losses and complicated design of output filters. On the other hand, with large penetration of renewable energy in power systems, the power converters have become more and more large-scale and complex.

It is obviously not adequate only using the traditional SMC techniques to control these large-scale converters in the future. Therefore, the integration of intelligent control, multi-agent and data-driven approaches with SMC will become one of the most promising researches in control and power electronics fields. By designing properly, these seminal composite control schemes can enhance the performance of the SMC and simultaneously capture attractive features of the advanced algorithm, which can be extensively applied to control complex power electronics systems and does have a huge potential in industrial applications.

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