Adaptive total sliding mode control for the current of power factor correction circuit

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Abstract: The design of an adaptive total sliding mode control (ATSMC) system for the current control of power factor correction (PFC) is addressed in this paper. The designed ATSMC can achieve elegant performance under ideal condition as well as the existence of parameters variations, moreover, the designed controller parameter is adjusted adaptively to overcome the potential chattering. The merits of the designed ATSMC is verified by a boost type PFC prototype, the simulation and experiment results show that the PFC circuit can achieve unity power factor and sinusoidal grid current, simultaneously, the output voltage has well dynamic and steady state performance.

Keywords: power factor correction (PFC), adaptive total sliding mode control (ATSMC), charging devices, electric vehicles (EV)

Classification: Power devices and circuits

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1 Introduction

A large number of harmonics current will be generated in ac-side, when uncontrolled rectifier bridge is used in charging devices of electric vehicles, which has negative effect on the load as well as components of the main circuit [1]. Power factor correction (PFC) circuit force the input current to track the voltage waveform in the power supply network, so as to achieve the targets containing sinusoidal input current, unity power factor in input side and stable DC output voltage, finally, electric power transformation efficiency is improved [2]. Therefore, in order to improve the charging performance of electric vehicles and reduce impact to the power quality of utility grid, PFC plays a very important role in AC/DC converter [3].
IC designed for PFC has been developed, which can implement multiple functions, including soft start, under-voltage protection of input power supply [4]. However, the designs using IC should be based on the IC specification and the limit operating conditions containing small parameter-adaptation-range, various components in control circuit and poor adaptability should be considered, moreover, it is susceptible to noise interference, and the debugging process is complicated [5]. Compared with analog control technology, digital control technology has merits of fewer components in actual circuit, small noise interference and reliable control. In addition, the digital control converter can also improve the dynamic response performance of the control system [6, 7]. However, the control methods focus on the reduction of harmonic current in ac-side and fast tracking of voltage phase without considering the influence of parameter variations or load disturbance.

PFC circuit is a typical nonlinear system, due to the existence of nonlinear element in circuit and switching variable in state space model, it is hard to achieve well performance using traditional linear control strategy. Sliding mode control (SMC) is an effective control method for nonlinear system [8], the control quantities can be changed continuously according to the current state of system, which allowing system state moving to the equilibrium point along the preset sliding surface after reaching the sliding mode [9]. SMC is especially suitable for switching mode system control [10], it has been successfully applied in the control of DC-DC converters [11], when disturbances are existed in the system before reaching the sliding surface, the sliding process may not be completed, which may bring about the system uncontrollable. Aiming at this problem, the total sliding mode controller (TSMC) is designed in literature [12], the initial states of the system can be included in the designed sliding surface, so the stability of all system states can also be ensured when system uncertainties exist. The control force designed in view of system uncertainties would cause chattering, thus the adaptive algorithm is used to estimate and adjust the boundary of uncertainties, and the system dynamic characteristics have very strong robustness in uncertainty [13].

The paper is organized into 5 sections, following the introduction, the circuit framework and state space mode of the boost-type PFC circuit are described in Sect. 2. Then, in Sect. 3. the design procedure of ATSMC is analyzed in detail. Simulation and experiment results of the boost-type PFC prototype controlled by DSP 28335 are carried out to demonstrate the effectiveness of designed ATSMC in Sect. 4. Finally, some conclusions are given in Sect. 5.

2 Boost-type PFC circuit descriptions

The circuit framework of boost-type PFC circuit is show in Fig. 1. Where \( r_L \) is the equivalent resistance of inductance, \( S \) is the main switch, \( D \) is the output diode, \( C \) is the output capacitor, \( R_L \) is the load resistor; \( i_L \), \( v_o \) are the inductor current and DC output voltage, respectively.

When \( S \) is on, the inductor \( L \) is in the energy storage process, and the capacitor \( C \) provide energy to the load \( R_L \), the current path is shown as imaginary line in Fig. 1; When \( S \) is off, the inductor \( L \) is in the process of releasing energy to the capacitor \( C \) and the load \( R_L \), the current path is shown as dash-dotted line in Fig. 1,
the ESR of $C$ is neglected, the ideal state-space average mathematical model of PFC can be written as follows

$$L \frac{di_L}{dt} = v_{in} - i_L r_L - (1 - d)v_o$$  \hspace{1cm} (1a)$$

$$C \frac{dv_o}{dt} = (1 - d)i_L - \frac{v_o}{R_l}$$  \hspace{1cm} (1b)$$

where $v_s = V_s \sin \omega t$ is the grid voltage; $i_s$ is the grid current; $v_{in} = |V_s \sin \omega t|$ is the output of uncontrolled rectifier; $|\bullet|$ is the absolute value operator; $L$ is the input inductor, $d$ is the duty ratio of the switch $S$.

Generally, the parameters $L$, $C$, $R_l$ and $v_{in}$ in (1) are often regarded as ideal constants, while in practical applications, they may not equal to the nominal value, this paper aim to design a current controller for PFC to improve the robustness against the parameter variations. So, considering the variations of parameters, they can be expressed with nominal value and variations, and the state space model of current in (1a) can be modified as

$$i_L(t) = -\frac{r_{Ln} + \Delta r_L}{L_n + \Delta L} i_L(t) - \frac{1 - d}{L_n + \Delta L} v_o(t) + \frac{1}{L_n + \Delta L} (v_{in}(t) + \Delta v_{in}(t))$$

$$\triangleq A_p i_L(t) + B_p u_{con}(t) + D_p v_{in}(t)$$

where $i_L(t)$ is taken as the controlled state variables, and $u_{con}(t) = (1 - d)v_o$ is the control effort of the current control system. $A_p = -\frac{r_{Ln} + \Delta r_L}{L_n + \Delta L}$, $B_p = -\frac{1}{L_n + \Delta L}$, $D_p = \frac{1}{L_n + \Delta L}$, $A_p$, $B_p$, $D_p$ is the nominal values of $A_p$, $B_p$, $D_p$ respectively; $\Delta A_p$, $\Delta B_p$, $\Delta D_p$ denote the system parameter variations; $w(t)$ is the lumped uncertainty, and defined as

$$w(t) = \Delta A_p i_L(t) + \Delta B_p u_{con}(t) + \Delta D_p v_{in}(t).$$

The bound of the lumped uncertainty is assumed to be given, the absolute value $|w(t)| < \rho$, $\rho$ is a given positive constant.

### 3 ATSMC design for current control of PFC

Based on the state-space model of current expressed in (2), adaptive total sliding mode controller (ATSMC) will be designed, which can force the current of inductor to track a given command under ideal conditions as well as system uncertainties, therefore, a sinusoidal grid-current in phase with the grid voltage can be gain, and the power factor can be improved.
The objective of the SMC for the current control of PFC is to force the system state $i_L$ to track a reference current $i_{Lr}$, $e_i = i_L - i_{Lr}$ is defined as the tracking error of inductor current, and its derivative is $\dot{e_i} = \dot{i}_L - \dot{i}_{Lr}$. The baseline model of inductor current can be expressed as

$$\dot{i}_L(t) = A_{pn}i_L(t) + B_{pn}u_{con}(t) + D_{pn}v_{in}(t) \quad (4)$$

An integral type sliding surface is selected as

$$s(t) = e_i(t) - e_i(0) - k \int_0^t e_i(\tau)d\tau \quad (5)$$

where $e_i(0)$ is the initial value of $e_i(t)$, and $k$ is a nonzero positive constant.

A control law of the baseline model can be designed as follows:

$$u_{comb} = -B_{pn}^{-1}[A_{pn}i_L + D_{pn}v_{in} + k e_i - \dot{i}_{Lr}] \quad (6)$$

Substituting (6) to the baseline model, the controlled nominal system dynamics are

$$\dot{e}_i + k e_i = 0 \quad (7)$$

Equation 7 shows that the inductor current control system is a first-order system, properly choosing the values of $k$, the desired system dynamics can easily be designed [13]. And $s(t) = 0$ for all $t \geq 0$ under baseline model, which means there is no reaching time compared to the traditional SMC because the system state is on the sliding surface at $t = 0$, the designed system has a total sliding motion for all time [12, 14].

However, if uncertainties occur, the parameters of the system deviate from the nominal value or an external load disturbance is added into the system, the baseline model design cannot guarantee the performance, the stability of the controlled system may be destroyed [13].

If the unknown parameter variations and external load disturbance occur, the system dynamics should consider the lumped uncertainty, which can be expressed as follow

$$\dot{i}_L(t) = A_{pn}i_L(t) + B_{pn}u_{con}(t) + D_{pn}v_{in}(t) + w(t) \quad (8)$$

It is obvious that the control law $u_{comb}$ shown in (6) cannot ensure the baseline model performance, and it is necessary to design an additional control law so that the performance of the uncertain PFC control system has the same dynamic performance depicted in (7).

A new sliding surface is selected as

$$s(t) = f(e_i(t)) - f(e_i(0)) + k \int_0^t \frac{\partial f}{\partial e_i} e_i(\tau)d\tau \quad (9)$$

where $f(e_i(t))$ is needed to be designed. It is can be seen that

$$\dot{s}(t) = \frac{\partial f}{\partial e_i} \dot{e}_i(t) - k \frac{\partial f}{\partial e_i} e_i(t) = \frac{\partial f}{\partial e_i} (\dot{e}_i(t) - k e_i(t)) = 0 \quad (10)$$

According to (8) and (10) in order to achieve the required dynamic performance like (7), the control law should be designed as

$$u_{con} = u_{comb} + u_{conc}$$

$$= -B_{pn}^{-1}[A_{pn}i_L + D_{pn}v_{in} + k e_i - \dot{i}_{Lr} - \rho \text{sgn}(s(t))] \quad (11)$$

where the additional control law is expressed as
If the condition of

where \( \text{sgn}(\ast) \) is a sign function, \( \rho \) is the estimate parameter which is a positive constant.

Under the control law is given by (11), the tracking error of inductor current can be always kept on the sliding surface with

\[
s(t) = f(e_i(t)) - f(e_i(0)) + k \int \frac{\partial f}{\partial e_i} e_i(t) dt = 0
\]

where \( f \) satisfies \( \frac{\partial f}{\partial e_i} = B_{pm}^{-1} \).

Substituting (11) to (8), the derivative of tracking error of inductor current can be obtained as

\[
\dot{e}_i(t) = -ke_i(t) + B_{pm}(u_{\text{conc}} + B_{pm}^{-1}w(t))
\]

A Lyapunov function candidate is defined as \( V_1 = 0.5s^2 \), according to (12) and (13), the derivative of \( V_1 \) is expressed as

\[
\dot{V}_1 = s(t)\dot{s}(t)
\]

\[
= -B_{pm}^{-1}\rho \text{sgn}(s(t))s(t) + B_{pm}^{-1}s(t)w(t)
\]

\[
\leq -B_{pm}^{-1}\rho |s(t)| + B_{pm}^{-1}|s(t)||w(t)|
\]

\[
\leq -B_{pm}^{-1}(\rho - |w(t)|)|s(t)|
\]

If the condition of \( \rho > |w(t)| \) can be satisfied, \( \dot{V}_1 \leq 0 \) will be established, that is \( \dot{V}_1 \) will be a negative-definite function. It implies that the tracking error of inductor current \( e_i \) will go to zero asymptotically according to the Lyapunov theorem. Thus, the stability of the total sliding mode control can be guaranteed.

Equation 15 shows that, the stability of the total sliding mode control is effected by the control gain \( \rho \), only \( \rho \) is selected larger than the bound of the lumped uncertainty, can the stability be guaranteed. Unfortunately, it is difficult to measure the bound of the lumped uncertainty in practical applications. Usually, the control gain \( \rho \) is designed as large as possible to ensure the stability of the control system, however, a large control gain may cause chattering phenomenal. As an alternative, an adaptive algorithm can be used to estimate the bound of the lumped uncertainty [13].

One can select the adaptive algorithm as follows

\[
\dot{\rho} = \frac{1}{\lambda} B_{pm}^{-1}|s(t)|
\]

where \( \hat{\rho} \) is the estimate value of \( \rho \), an estimate error is defined as \( \hat{\rho} = \rho - \hat{\rho} \), in order to force the \( \hat{\rho} \) tend to zero, consider the second Lyapunov function \( V_2 = 0.5s^2 + 0.5\hat{\rho}^2 \), and the derivative of \( V_2 \) can be presented as:

\[
\dot{V}_2 = s(t)\dot{s}(t) + \hat{\rho}\dot{\rho}(t)
\]

\[
= -B_{pm}^{-1}s(t)[\hat{\rho}\text{sgn}(s(t)) - w(t)] + \frac{1}{\lambda}B_{pm}^{-1}s(t)[\hat{\rho}(t) - \rho]
\]

\[
= -B_{pm}^{-1}[\hat{\rho}d\text{sign}(s(t)) - s(t)w(t)] + \frac{1}{\lambda}B_{pm}^{-1}s(t)[\hat{\rho}(t) - \rho]
\]

\[
= B_{pm}^{-1}s(t)\dot{w}(t) - B_{pm}^{-1}\rho|s(t)|
\]

\[
\leq B_{pm}^{-1}|s(t)||w(t)| - B_{pm}^{-1}\rho|s(t)|
\]

\[
= -B_{pm}^{-1}(\rho - |w(t)|)|s(t)|
\]
If the condition of \( \rho > |w| \) can be satisfied, that is \( \rho > \rho_i \), \( \dot{V}_2 \) will be a negative definite function \( \dot{V}_2 \leq 0 \), according to Lyapunov theorem and Barbalat’s lemma [14], the sliding surface \( s \) and estimate error \( \hat{\rho} \) will go to zero asymptotically, which implies that \( s \) and \( \hat{\rho} \) are bounded functions, the stability of ATMC for the current control of PFC can be guaranteed.

The designed ATSMC system for the current control of PFC is shown in Fig. 2, the DC output voltage is adjusted by utilizing a proportional integral controller (PIC), the output of PIC is used as the amplitude of the current reference, which multiply unity semi-sine from grid voltage to generate the current reference, the designed ATSMC force the inductor current to track the reference, the control effort from ATSMC is compared with a triangular carrier signal to generate a PWM signals for the semiconductor switching devices.

4 Numerical simulation and experimental results

4.1 Numerical simulation results

The performance of the designed ATSMC system for the PFC is verified by the numerical simulations in the PSIM software compared with the traditional proportional integral control (PIC). The circuit parameters used in simulations are listed in Table I.

| System Parameters                  | Symbol | Value    |
|------------------------------------|--------|----------|
| Grid line voltage (RMS)            | \( V_S \) | 110 V    |
| Grid voltage frequency             | \( f \) | 60 Hz    |
| Load resistance                    | \( R_I \) | 200 \( \Omega \) |
| Grid filter inductance             | \( L \) | 1.48 mH  |
| Grid filter resistance             | \( r_L \) | 0.1 \( \Omega \) |
| DC-bus capacitor                   | \( C \) | 1 mF     |
| Switching frequency                | \( f_s \) | 40 kHz   |

Fig. 2. Block diagram of ATSMC system.
Fig. 3 shows the dynamic and steady-state performance of the output voltage under ATSMC when the reference voltage is 200 V, it is obviously, the output voltage can track the reference command with quick dynamic response and high control accuracy.

The steady-state performance of inductor current is depicted in Fig. 4. For the sake of observation, the inductor current multiplied by five is shown with the input voltage of boost converter, the inductor current can be controlled to be in phase with the input voltage of boost converter, and there is no dead zone in inductor current.

In order to verify the power factor correct result, the grid current and voltage are shown in Fig. 5(a), the steady-state performance controlled by ATSMC is depicted as 5 times grid current. The comparison-simulation experiment is done between ATSMC and PIC to validate the control effectiveness, the steady-state performance with PIC is shown in Fig. 5(b), it can be seen that, the grid current with ATSMC is a sinusoidal wave and in phase with the grid voltage, the power factor (PF) value is 0.994 and it is higher than the control effort with PIC.

Comparative analysis of dead zone at the crossover of grid current between ATSMC and PIC depicted in Fig. 6 shows that dead zone at the crossover is smaller with ATSMC, which means the grid current has better sinusoidal. The simulation result indicates that the designed ATSMC current controller can achieve the control target very well.

The robustness against parameter-variations is an important feature of the designed ATSMC, and the filter inductance $L$ is one of the important parameters.
in current control system, the simulation result with the actual inductance changing from 90% to 110% of the nominal value 1.48 mH with ATSMC and PIC are depicted in Fig. 7, the numerical simulation result show that the PF value ranged from 0.9927 to 0.995, that is, when the filter inductance varies 10% of the nominal value, while the PF value varies less than 0.1% of the value under nominal inductance, the PF value is higher and the variation range is smaller with ATSMC compared with PIC.

4.2 Experimental results

In order to demonstrate the effectiveness of the designed ATSMC system, the practical photograph of experimental prototype is shown in Fig. 8, The PFC circuit parameters used in practical experimentation is the same as simulations which are
listed in Table I. The designed ATSMC control algorithm in the practical experimentation is carried out via the TMS320LF28335 DSP, and a sampling circuit is utilized to sense the voltages and current for closed loop control system.

The DC output voltage dynamic and steady-state waveform can be observed by the help of a YOKOGAWA oscilloscope. It can be seen from Fig. 9, the PFC worked as uncontrolled rectifier at beginning, when the PWM signal generated from DSP control board is acted on the Semiconductor switching S via the designed ATSMC algorithm, the DC output voltage can track the command quickly without voltage overshoot.

The experimental result of the current control system based on ATSMC is shown in Fig. 10, the waveform of inductor current is a positive semi-sine, and it is in phase with the output voltage of rectifier voltage, that is the input voltage of the boost convert, the result shows that, the inductor current can track the reference
current well, this validate the control effectiveness of the designed ATSMC for inductor current.

Fig. 10. Experimental result of the current control system based on ATSMC.

Fig. 11 shows the experimental result of the grid current, the result of the experimentation indicate that the designed ATSMC can achieve a good sinusoidal grid current, and the grid current is in phase with the grid voltage, the target of improving the PF value can be guaranteed.

Fig. 11. Experimental result of the grid current.

5 Conclusion

This paper demonstrated the design of the ATSMC to control the inductor current of a PFC circuit. The PFC circuit framework of the PFC circuit and its state space mode with system uncertainties was described, the design process was introduced in detail. Finally, numerical simulations and practical experimental results is utilized to indicate the performance of the designed ATSMC system, according to the numerical simulation results, the DC output voltage can track the command quickly without voltage overshoot, the grid current can be sinusoidal and in phase with grid voltage, the control target of near unity power factor is achieved with the designed ATSMC system, moreover, the comparison-simulation experimental with a traditional PIC results show that the PF value is higher, the dead zone at the crossover is smaller and the better robustness against the variation of filter inductance. Both numerical simulation results and practical experimental results validate the effectiveness the designed ATSMC system.
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