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Lyapunov-Based Adaptive Sliding Mode Controller for Active Power Filter

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Abstract: In this paper, a Lyapunov-based adaptive 2nd-order sliding mode controller is proposed to control the current in an active power filter (APF). The penetration of APFs has been exponentially increased because of their high flexibility and fewer resonance problems. Moreover, they can compensate high range of current harmonics and reactive power. The voltage and current control loops have always been interesting areas for researchers since the satisfactory performance of the APF is highly dependent on these control loops. A sliding mode controller (SMC) is a mighty controller when uncertain conditions are considered. However, in order to reduce the chattering- high-frequency switching- and improve the steady state operation, stability, and robustness of the controller, it is usually decided to adaptively tune the gains of the controller. In this paper, a simple-structure adaptive SMC (ASMC) is proposed which can be implemented easily. This ASMC is shown to be stable using the Lyapunov theorem and proved with SIMULINK simulation that it has less steady state error, less chattering, and faster dynamic response compared to the conventional SMC.

Keywords: Active Power Filter, Adaptive, Robustness, Sliding Mode Controller, Stability

1 Introduction

POWER quality (PQ) is usually referred to the deviation of voltage, current, and frequency from to permissible range. This deviation might lead to fault in power devices and losses. Therefore, researches have focused on design and implementation of devices which can improve the PQ level of the power system. DFACTS are popular devices that can be used for various sorts of PQ problems and have been proven to be effective [1,2]. The conventional approach to reduce the effects of PQ problems are passive filters that contain different kinds of connection (Delta, Wye, and combination of them) of inductors and capacitors. Those filters, however, suffer from fixed compensation, large size, and the probability of resonance. Due to their advantages compared to passive filters, active power filters (APFs) developed to further compensate the PQ problems. Using APFs, several sorts of PQ issues such as current harmonics, reactive power, load balancing, and neutral current compensation have been tackled properly. APFs can be connected either in series with power system or shunt. The former will compensate voltage distortions and the latter current deviations. These two structures can also be mixed so that unified power quality conditioner results. Sometimes, in order to have the advantages of both active and passive filters, they are combined and referred as hybrid power filters [3,4].

Output filter of an APF is a popular field to study. Various sorts of filters have been applied to an APF to gain certain features. A structure which reduces the DC voltage needed for APF is a series LC filter connected to the APF. This LC-APF operates with less DC-voltage and as a result, the voltage stress on power switches and switching losses will decrease [5]. In [6], a fuzzy linear active disturbance rejection controller (Fuzzy-LADRC) is applied to an injected hybrid active power filter (IHAPF). This controller contains a fuzzy proportional controller, a linear extended state observer (LESO), and a total disturbance compensation link and

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eventually leads to lesser tracking error and more robustness in disturbance circumstances. In [7], an efficient techno-economical approach is adopted in order to alleviate harmonics and enhance the power factor in power distribution system using Shunt Hybrid Active Power Filters (SHAPF) based on neural network algorithms. In this method, the results of detecting harmonics are compared with conventional pq0 theory. In addition, the regulation of DC bus of the SHAPF, is done using conventional PI controller and neural networks-based controllers and the outcome is compared. It is finally shown that RNN algorithm is the best choice for this purpose and gives satisfactory results.

In [8], SVC-APF is proposed to improve the PQ of the power system. SVC consists of a thyristor-controlled LC filter that can change the impedance of the filter according to the firing angle of the thyristors. In an APF, it is important to keep the DC-link voltage in a certain range to ensure the proper performance of the device. Therefore, several controllers are designed to improve the voltage regulation of the APF. In [9], a PID controller if used for this purpose, but the coefficients of the PID controller is tuned using a hybrid GWO-PSO optimization algorithms. In [10] a fractional sliding mode controller combined with recurrent neural network is presented to estimate the unknown functions of an APF. This method resulted in better compensation of the system and improved robustness.

The authors in [11] state that the dynamic performance of an APF is a key point and thus, they propose a finite control set model predictive control (FCS-MPC) to enhance the dynamic compensation of reactive power. In [12], an APF is controlled using direct power control method along with dead-beat control. Moreover, the dead-beat controller is enhanced so that the effects of delays caused by digital implementation are reduced. In [13], a control strategy which contains a feedback-linearization-type approach to is applied to an APF which intends to control the filter currents, whereby the voltage control loop is decoupled from the current control. The main idea, however, is to compensate the one-sampling-period delay caused by microcontroller computation using a finite impulse response (FIR) predictor.

Sliding mode controller (SMC) is considered an effective controller especially in the presence of uncertainty. The main idea of SMC is to keep moving on a sliding surface using high-frequency switching. However, this high-frequency switching causes practical problems named chattering and needs to be modified. To tackle the issues of 1st order SMC, it is common to use 2nd order ones, such as sub-optimal controller, terminal SMC, twisting controller, and super-twisting controller [14]. In [15], a super-twisting SMC (STSMC) is proposed based on observation to control the DC-link voltage of an APF. A linear Kalman filter is used as well, for robust estimation which uses a phase angle vector model to ease the implementation pf the PLL. In order to achieve the advantages of both dynamic SMC and terminal SMC, [16] has combined them. Thus, the chattering problem has been alleviated. In addition, a double hidden layer recurrent neural network is also exploited to approximate the proposed SMC. The approximation error of the neural network has been also eliminated using an extra integral robust switching term.

In [17], a global SMC is investigated to track the reference current in an APF. In order to tackle the issue of the unavailable uncertain parameters in an APF, a recurrent feature selection neural network is proposed in [17] to learn uncertain functions. This neural network can select between worthwhile and unfavorable parameters of the neural network. The authors in [18] also present a SMC applied to a bridgeless boost converter as the voltage control loop to improve the dynamic performance, stability, and attenuate the output voltage ripple. In [19], the idea of adaptive SMC is extended based on a long and short-term memory fuzzy neural network (ASMC-LSTMFNN) and used to approximate the unknown functions is a single-phase APF. Since the fuzzy neural network (FNN) structure and long and short-term memory (LSTM) mechanism are combined, excellent learning ability and approximation performance is obtained.

In [20], a novel deadbeat-based direct power control solution is proposed to synthesize reference current and control of APF. Furthermore, a simple and robust compensation approach is exploited to remove aforementioned deadbeat delay using online/offline predictions. In [21], a SMC is used in an APF, along with a new type of long and short-term memory fuzzy neural network to approximate the unknown functions of the system. This approximation method has mighty learning ability and estimation. In [22], an adaptive SMC is proposed to control the speed of a switched reluctance motor which produces the reference torque for the motor. In [23], in order to overcome the nonlinearities and uncertainties in an induction generator, and an adaptive dynamic SMC is proposed.

In [24], a 2nd order SMC based on super-twisting controller is presented as a current controller for a three-phase APF. This super-twisting SMC (STSMC) firstly provides a fixed switching frequency and secondly, better stability and performance. The present paper improves the performance of the STSMC proposed in [24] by using an adaptive mechanism to adaptively tune the STSMC gains. This adaptive SMC (ASMC) is based on Lyapunov theorem which ensures the stability of the controller. Moreover, unlike the aforementioned ASMCs which mainly used neural network, the proposed ASMC exploits a different approach. Thus, there is no need to bulky data-base and learning process which leads to less expensive processing unit and simplicity of the implementation of the controller on the digital processor.

The main contributions of this paper are:

- Proposing an adaptive sliding mode controller for an active power filter current control
- Using Lyapunov theorem in designing the adaptive mechanism and hence, ensuring the stability
- A simple adaptive mechanism with no need to data-base and learning system unlike some adaptive controllers based on gathered data from system such as ANFIS and artificial intelligence.
- Easy to implement controller since the adaptation laws need only one integral in calculating he coefficients.

The rest of this paper contains:

The configuration of the system is provided in section II. Section III presents the control scheme for the APF which consists of two parts. In the first part, Generating the reference currents is explained and in the second section, the ASMC is designed to track the reference current. The simulation results are provided in section IV and a brief conclusion of the work is given in section V.

2 Hardware Configuration

Fig.1 shows the overall configuration of an APF. In Fig.1, C is the DC-link capacitor of the APF, V_{dc} is the DC-link-voltage, Q_1 to Q_4 are power switches of the inverter, L is the output filter and R shows its internal resistance, V_s is the voltage source, i_c is the compensating current and i_L is the load current.

3 Control method of the APF

In this paper, the instantaneous reactive power theory (IRPT) is used to generate the harmonic and reactive part of the load current. By generating the harmonic and reactive part, and using the reverse Clarck transformation, the reference current will be synthesized.

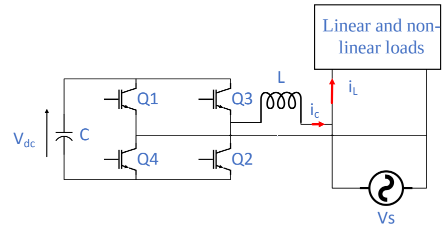

Fig. 1 System configuration

Then, the current controller makes the switching signals so that the actual current tracks the reference current. It is worth noticing that the voltage controller provides a signal that represents the positive or negative power needed for DC-link voltage regulation. This power signal is added to the active power which is to be compensated.

3.1 Reference Current Generation

As stated before, the aim of IRPT is to generate the signals representing the harmonic and reactive parts of the load current. In order to reach this goal, the load current and source voltage are measured. To convert these signals to $\alpha\beta$ frame, they have to be shifted by 90 degrees. Therefore, the original signal is the α -axis and the shifted signal is the β -axis [25]. To be more precise:

$$i_\alpha = i_L \quad , \quad i_\beta = i_L(90^\circ shift) \tag{1}$$

$$V_\alpha = V_s \quad , \quad V_\beta = V_s(90^\circ shift) \tag{2}$$

According to the IRPT theory, the instantaneous active and reactive power can be obtained by [25]:

$$P_{\alpha\beta} = V_\alpha i_\alpha + V_\beta i_\beta \tag{3}$$

$$Q_{\alpha\beta} = V_\alpha i_\beta - V_\beta i_\alpha \tag{4}$$

where $P_{\alpha\beta}$ and $Q_{\alpha\beta}$ are instantaneous active and reactive powers. Both active and reactive powers consist of two parts; i.e. a dc part and an oscillating part. The former shows the fundamental frequency current and the latter represents for the harmonic currents.

$$P_{\alpha\beta} = \bar{p} + \tilde{p} \tag{5}$$

$$q_{\alpha\beta} = \bar{q} + \tilde{q} \tag{6}$$

In Eq. (5) and Eq. (6), $\tilde{p}$ and $\tilde{q}$ are oscillating parts of the active and reactive power, respectively. In addition, $\bar{p}$ and $\bar{q}$ are constant parts. The parts which are to be compensated are whole the reactive power and the oscillating part of active power. The oscillating part of the active power can be extracted using a high pass filter.

As stated before, the voltage controller is a PI controller in which the input is the DC-link voltage error. The PI controller produces a signal corresponding to the positive or negative power needed to regulate the DC-link voltage as shown below:

$$e_v = V_{dc} - V_{dcref} \tag{7}$$

$$P_{loss} = K_p e + K_i \int e\,dt \tag{8}$$

where e_v is the voltage error, K_p and K_i are the proportional and integrator gains, respectively, V_{dcref} is the reference DC-link voltage, and P_{loss} is the power signal responsible for DC-voltage regulation. This loss signal is added to previously obtained $\tilde{p}$.

Hence, according to Eq. (5) to Eq. (8), the reference active and reactive power can be described as:

$$\mathrm{P}_{ref} = \tilde{p} + P_{loss} \tag{9}$$

$$Q_{ref} = q_{\alpha\beta} \tag{10}$$

Furthermore, the inverse Clarck transformation is used to convert active and reactive powers into $\alpha\beta$ frames.

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \times \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} . \begin{bmatrix} -\mathrm{P}_{ref} \\ -Q_{ref} \end{bmatrix} \tag{11}$$

Once the reference current is generated, the current controller is used to track this reference current. The principle of the proposed ASMC is expressed in the next section.

3.2 Adaptive Super-Twisting Sliding Mode Controller

In order to track the reference current, the super-twisting proposed in [24] is used due to its simplicity and suitable performance. However, to improve the dynamic performance of the controller and to increase the stability and robustness of it, the gains of the controller are tuned adaptively. The mechanism of adaption is based on Lyapunov theorem which results in simplicity and less computational load and database compared to neural network-based adaption mechanisms. To design the adaptive controller, the model of the system is written as:

$$L\dot{i}_c = -Ri_c + V_s - V_{dc}u \tag{12}$$

where u is the control signal. By modifying Eq. (15), the model can be re-written as:

$$\dot{i}_c = \frac{-R}{L} i_c + \frac{1}{L}\left(V_s - V_{dc}u\right) \tag{13}$$

The following aliases are set to simplifying the mathematical calculations:

$$i_c = y\ , \dot{i}_c = \dot{y}\ , \frac{-R}{L} = a \qquad \frac{1}{L} = b \quad , V_s - V_{dc}u = u' \tag{14}$$

Hence, Eq. (13) can be described as:

$$\dot{y} = ay + bu' \tag{15}$$

The desired model is defined as:

$$\dot{y}_m = a_m y_m + b_m u_c \tag{16}$$

According to [24], the control law is based on the super-twisting controller and is chosen to be:

$$u = k_1 sign(e)\,|\sqrt{e}\,| + k_2 \int sign(e)dt \tag{17}$$

where k_1 and k_2 are controller gains and e is the error between the reference and actual currents. Thus, the closed loop model of the system would be:

$$\dot{y} = ay + b\left(k_1 sign(e)\,|\sqrt{e}\,| + k_2 \int sign(e)dt\right) \tag{18}$$

The time derivative of the error signal, e , can be expressed as:

$$\begin{aligned} \dot{e} &= \dot{y}_m - \dot{y} \\ &= a_m y_m + b_m u_c - ay \\ &\quad - b\left(k_1 sign(e)\,|\sqrt{e}\,| + k_2 \int sign(e)dt\right) \end{aligned} \tag{19}$$

Since the reference model is set by the designer, it is assumed that $a_m = a, b_m = 0$. Thus, Eq. (19) will be as:

$$\dot{e} = ae - b\left(k_1 sign(e)\,|\sqrt{e}\,| + k_2 \int sign(e)dt\right) \tag{20}$$

In order to prove the stability and to obtain the adaption law, the Lyapunov function is defined as:

$$\begin{aligned} V &= \frac{1}{2}e^2 + \frac{1}{2\gamma}\left(bk_1 sign(e)\,|\sqrt{e}\,|\right)^2 \\ &\quad + \frac{1}{2\gamma}\left(bk_2 \int sign(e)dt\right)^2 \end{aligned} \tag{21}$$

where γ is the converging rate. The first derivative of Eq. (21) is calculated as:

$$\begin{aligned} \dot{V} &= e\dot{e} + \frac{1}{\gamma}\left(bk_1 sign(e)\,|\sqrt{e}\,|\right)\left(b\dot{k}_1 \left(sign(e)\right)' \left(|\sqrt{e}\,|\right)'\right) \\ &\quad + \frac{1}{\gamma}\left(bk_2 \int sign(e)dt\right)\left(b\dot{k}_2 sign(e)\right) \end{aligned} \tag{22}$$

By substituting $\dot{e}$ from Eq. (20) into Eq. (22):

$$\begin{aligned} \dot{V} &= e\left(ae - b\left(k_1 sign(e)\,|\sqrt{e}\,| + k_2 \int sign(e)dt\right)\right) \\ &\quad + \frac{1}{\gamma}\left(bk_1 sign(e)\,|\sqrt{e}\,|\right)\left(b\dot{k}_1 \left(sign(e)\right)' \left(|\sqrt{e}\,|\right)'\right) \\ &\quad + \frac{1}{\gamma}\left(bk_2 \int sign(e)dt\right)\left(b\dot{k}_2 sign(e)\right) \end{aligned} \tag{23}$$

By modifying Eq. (23), it will be concluded that:

$$\dot{V} = ae^2 + \left(bk_1 sign(e)|\sqrt{e}|\right)\left(-e + \frac{1}{\gamma}\left(b\dot{k}_1 \left(sign(e)\right)'\left(|\sqrt{e}|\right)'\right)\right) + \left(bk_2 \int sign(e)dt\right)\left(-e + \frac{1}{\gamma}\left(b\dot{k}_2 sign(e)\right)\right) \quad (24)$$

In order to have a stable controller, all terms of Eq. (24) should be negative or zero. Since $a < 0, e^2 > 0$, the first term of Eq. (24) is always negative. The other terms should satisfy the following equality:

$$-e + \frac{1}{\gamma}\left(b\dot{k}_1 \left(sign(e)\right)'\left(|\sqrt{e}|\right)'\right) = 0 \quad (25)$$

$$-e + \frac{1}{\gamma}\left(b\dot{k}_2 sign(e)\right) = 0$$

By simplifying Eq. (25), the coefficients of the controller can be calculated as:

$$\dot{k}_1 = \frac{e\gamma}{b\left(sign(e)\right)'\left(|\sqrt{e}|\right)'} \quad (26)$$

$$\dot{k}_2 = \frac{e\gamma}{bsign(e)}$$

Using MATLAB workspace, the derivatives of $sign(e), \left|\sqrt{e}\right|$ are:

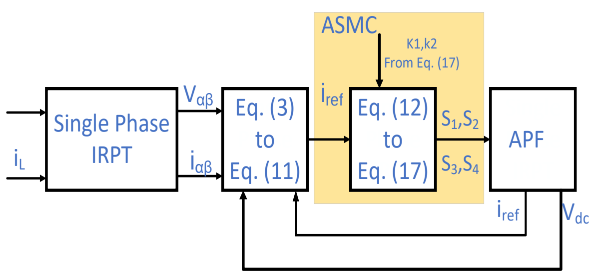

Fig. 2 Control scheme

$$\left(sign(e)\right)' = 2\delta(e) \quad (27)$$

$$\left(|\sqrt{e}|\right)' = \frac{sign(e)}{2|\sqrt{e}|}$$

Thus, the coefficients will be:

$$\dot{k}_1 = \frac{e\gamma|\sqrt{e}|}{b\delta(e)sign(e)} \quad (28)$$

$$\dot{k}_2 = \frac{e\gamma}{bsign(e)}$$

The overall control block diagram of the ASMC is provided in Fig2.

4 Simulation Results

In this section, the performance of a single phase APF with the proposed ASMC is investigated using MATLAB-SIMULINK. The aim is to ensure the satisfying compensation of the harmonic currents and reactive power while the controller's stability and robustness have been improved by adaptively tuning the controller coefficients. The system parameters are as described in Table.1.

Table 1 System parameters

V_s (rms)	220 V
f_s	50 Hz
V_{dc}	380 V
L	5 mH

Fig.3 shows the operation of the APF with conventional SMC. It can be observed that at 0.1s, when the APF is Connected to the grid, the source current is compensated to that the current is almost sinusoidal. The load current THD is about 35% whilst the source current reduces to about 9% when APF is operating. The reactive power is also compensated by the APF. Besides, the inverter current has an error of nearly 0.2A since the current controller is not adaptive. Although, some distortion from the reference current can be observed in this situation which in high amounts of current can be harmful.

Fig.4 shows the operation of the APF with ASMC. In this circumstance, the controller's coefficients are adaptively tuned so that the controller is more robust and accurate. Moreover, the current tracking is more satisfactory from the point of view of THD. In this circumstance, the current THD is about 7% which is better than conventional SMC. Besides, the distortion from the reference current is completely eliminated. The reactive power is also compensated.

Fig.5 shows the operation of the APF under load change. The load is increased by nearly 50% at 0.2s. It can be observed that the controller has a satisfactory performance during and after load change and exactly follows the reference current even under high load changes.

Fig.6 shows the change in the controller coefficients during APF operation. It is obvious that by change in the circumstance, such as change in the load, the coefficients are tuned adaptively to achieve the best current tracking.

Fig.7 shows a comparison between SMC and ASMC from the point of view of steady state error. Fig.7(a) shows the current tracking of SMC and Fig.7(b) presents the performance of ASMC. It can be observed that ASMC has much less steady state error compared to the conventional SMC.

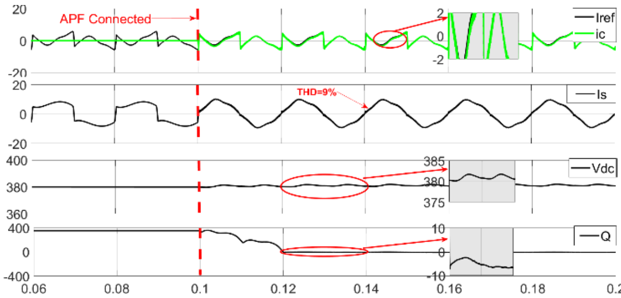

Fig. 3 APF operation with SMC

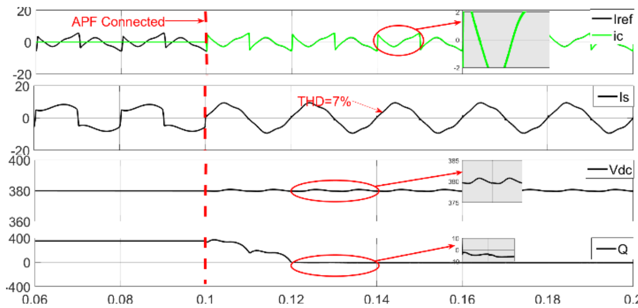

Fig. 4 APF operation with ASMC

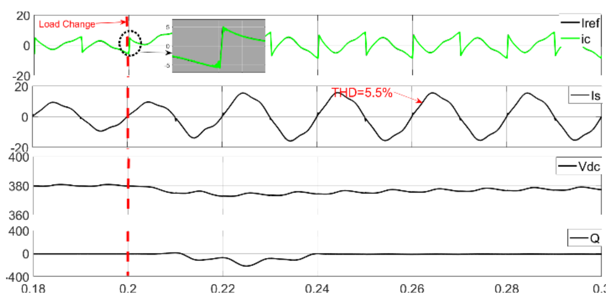

Fig. 5 APF operation with ASMC under load change

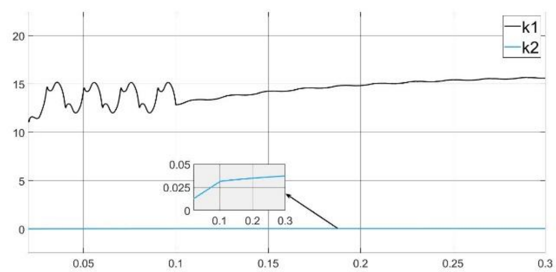

Fig. 6 Controller coefficients

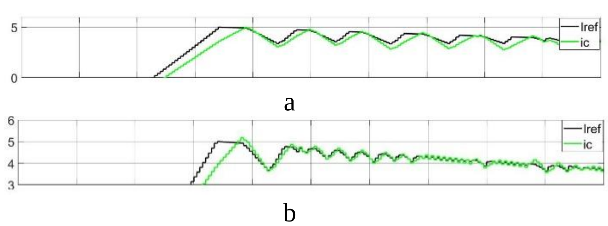

Fig. 7 Comparing steady state error of the current with: a) SMC, b) ASMC

5 Conclusion and Future works

In this paper, an adaptive sliding mode controller (ASMC) is proposed to track the reference current in an active power filter (APF). SMC is a powerful controller in non-linear systems with uncertainty, however, it suffers from variable switching frequency and chattering. By using ASMC, the gains of the controller are tuned adaptively which results into less chattering and steady state error, more robustness of the controller, and better harmonic compensation.

As a brief conclusion, it was shown that ASMC has more accurate tracking, more robustness against load change and gives better THD than conventional SMC. Another advantage of this approach is its simple adaption mechanism which is based on the Lyapunov theorem and therefore, the controller is much simpler to implement compared to the neural network-based controllers. The major contribution of this paper to the field is using simpler and less expensive CPUs in implementation of this structure. The practical challenges should also be regarded which are designing the output filters properly, minimizing the noise effect in the wiring and PCB design and etc. For the future works, one can enhance the voltage controller using novel intelligent methods, e.g. fuzzy algorithms, neural network, etc. Moreover, improved SMCs such as dynamic and terminal SMC can also be tested.

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