Sliding Mode Control Based Hybrid Active Filter with Variable Conductance for Harmonic Resonance Supression in Industrial Power Systems

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Abstract:
Unintentional series and/or parallel resonances, due to the tuned passive filter and the line inductance, may result in severe harmonic distortion in the industrial power system. This paper presents a hybrid active filter based on sliding mode controlling technique to suppress harmonic resonance and to reduce harmonic distortion. The operation mode of the active filter is detailed, introducing a new operating mode for the inverter in order to improve the behaviour of the line current during the zero-passing. The proposed hybrid filter is also operated as variable harmonic conductance according to the voltage total harmonic distortion; therefore, harmonic distortion can be reduced to an acceptable level in response to load change or parameter variation of the power system. Regarding sliding mode control, the sliding surface, the existence condition and the equivalent control are analyzed. The steady-state error is diminished by implementing a proposed sliding surface, which includes the current error and it’s integral. Since the hybrid filter is composed of a seventh-tuned passive filter and an active filter in series connection, both dc voltage and KVA rating of the active filter are dramatically decreased compared with the pure shunt active filter. In real application, this feature is very attractive since the active power filter with fully power electronics is very expensive. A reasonable trade-off between filtering performances and cost is to use the hybrid active filter. Design considerations are presented, and experimental results are provided to validate effectiveness of the proposed method. Simulations are carried out in MATLAB/ Simulink environment.

Index Terms: Harmonic resonance, hybrid active filter, industrial power system

List of symbols
\( V_{sA}, V_{sB}, V_{sC} \) source voltages at phase a, b, c
\( V_{S_{pn}} \) peak supply voltage
\( V_{dc} \) voltage across DC link capacitor
\( V_{ref} \) reference DC bus voltage
\( i_{sa}, i_{sb}, i_{sc} \) source currents at phase a, b, c
\( i_{sp} \) peak supply current
\( i_{sa}, i_{sb}, i_{sc} \) reference source currents at phase a, b, c
\( u_{pa}, u_{pb}, u_{pc} \) unit current vectors for phase a, b, c
\( f_n \) \( n^{th} \) harmonic frequency
\( X_{lR} \) inductive reactance at \( n^{th} \) harmonic freq.
\( X_{cR} \) capacitive reactance at \( n^{th} \) harmonic freq.
\( Q_C \) VAr size of capacitor
\( Q \) quality factor of inductive coil
\( s \) sliding surface
\( i_{sx} \) source current at phase \( x \), where \( x = a, b, c \)
\( i_{refx} \) reference current at phase \( x \), where \( x = a, b, c \)
\( v_{sx} \) source voltage at phase \( x \), where \( x = a, b, c \)

I. INTRODUCTION

Harmonic pollution is becoming increasingly serious due to extensive use of nonlinear loads, such as adjustable speed drives, uninterruptible power supply systems, battery charging system, etc. This equipment usually uses diode or thyristor rectifiers to realize power conversion because of lower component cost and less control complexity. However, the rectifiers will contribute a large amount of harmonic current flowing into the power system, and the resulting harmonic distortion may give rise to malfunction of sensitive equipment or interfering with communication systems in the vicinity of the harmonic sources. Normally, tuned passive filters are deployed at the secondary side of the distribution transformer to provide low impedance for dominant harmonic current flowing into the power system, and the resulting harmonic distortion may give rise to malfunction of sensitive equipment or interfering with communication systems in the vicinity of the harmonic sources. Normally, tuned passive filters are deployed at the secondary side of the distribution transformer to provide low impedance for dominant harmonic current and correct power factor for inductive loads [1], [2]. However, due to parameter variations of passive filters, unintentional series and/or parallel resonances may occur between the passive filter and line inductance. The functionality of the passive filter may deteriorate, and excessive harmonic amplification may result [3], [4]. Thus, extra calibrating work must be consumed to maintain the filtering capability.

Various active filtering approaches have been presented to address the harmonic issues in the power system

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The active filter intended for compensating harmonic current of nonlinear loads is the most popular one, but it may not be effective for suppressing harmonic resonances [8]. Bhattacharya and Divan proposed a hybrid series active filter to isolate harmonics between the power system and the harmonic source [9]. A so-called “active inductance” hybrid filter was presented to improve the performance of the passive filter [10]. Fujita et al. proposed a hybrid shunt active filter with filter-current detecting method to suppress the fifth harmonic resonance between the power system and a capacitor bank [11].

A hybrid filter in series with a capacitor bank by a coupling transformer was proposed to suppress the harmonic resonance and to compensate harmonic current [12], [13]. However, this method needs extra matching transformers or tuned passive filters to guarantee filtering functionality. Recently, a transformerless hybrid active filter was presented to compensate harmonic current and/or fundamental reactive current [14]–[19]. Design consideration of the hybrid filter for current compensation has been extensively studied. A hybrid active filter with damping conductance was proposed to suppress harmonic voltage propagation in distribution power systems [20]. Nevertheless, this method did not consider the resonance between the passive filter and the line inductance. The fixed conductance may deteriorate the damping performances. An anti-resonance hybrid filter for delta-connected capacitor bank of power-factor-correction applications was presented [21]. This circuit was limited to three single-phase inverters, and the filtering performance was not considered. In addition, the hybrid active filter was proposed for the unified power quality (PQ) conditioner to address PQ issues in the power distribution system [22]. Several case studies of the hybrid active filter considering optimal voltage or current distortion were conducted in [23]. In previous work, the authors have presented a transformerless hybrid active filter to suppress harmonic resonances in the industrial power system [24], [25]. The hybrid filter is constructed by a seventh-tuned passive filter and an active filter in series connection. It operates as a variable conductance at harmonic frequencies according to the voltage THD, so that harmonic distortion can be reduced to an acceptable level in response to load change and power system variation. Since the series capacitor is responsible for sustaining the fundamental component of the grid voltage, the active filter is able to operate with a very low dc bus voltage, compared with the pure shunt active filter [14], [20].

Hence, both the rated kVA capacity and the switching ripples are reduced accordingly. Moreover, the proposed harmonic conductance is able to avoid over current of the passive filter in the case of mistuning parameters. These features will benefit practical applications. In this paper, we further present designing consideration of the hybrid filter. A prototype circuit of the hybrid filter based on 55-V/4-kVA system has been established to verify theoretic analysis, including steady-state behaviour, transient response, and stability analysis.

The filtering performance of the hybrid filter is discussed considering X/R ratio and magnified variations of line impedance. We also focus on filtering deterioration due to line resistance, voltage unbalance, and capacitive filters in the power system. In many cases, an active power filter is designed to compensate harmonic current produced by a specific nonlinear load, in such a way that it needs to measure the load current to be compensated [14], [26]. In this paper, the active filter is designed as a harmonic conductance to suppress both harmonic resonance and harmonic distortion by using inverter-side voltage and current measurements. Notice that it does not require current information of the nonlinear loads. Thus, this approach can be suitable in power distribution networks in which the loads may be distributed along a feeder [20]. In addition, compensating fundamental reactive power due to unbalanced load is possible, but it is outside the scope of this paper [26], [27].

II. OPERATING PRINCIPLE

Synchronous Reference Frame Theory

The control system consists of reference current control strategy using SRF method. The SRF is performing the operation in steady-state or transient state as well as for generic voltage and current; it’s capable of controlling the active power filters in real-time system. Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation. The block diagram of the synchronous reference frame controller is shown in Fig. 2.
Proposed Control Strategy

The proposed control system consists of reference current control strategy using Sliding Mode Controller based method

The objective of controlling the hybrid active power filter is to provide compensating signal to the system in such a way, that the supply current waveform remain sinusoidal and at the same time the harmonic currents are supplied to the nonlinear load. It is done in three steps,

1. Signal conditioning.
2. Estimation of compensating signals.

The reference supply currents can be obtained by applying the filtering algorithm such as Instantaneous Reactive Power (IRP) theory, Synchronous Reference Frame (SRF) or by indirect method of sensing current. The instantaneous reactive power theory as is based on transformation from a-b-c reference frame to α-β reference frame of the instantaneous power, voltage and current signals. The methods based on IRP theory provide good compensation with zero time delay, but the circuit configuration is complex to implement. Synchronous reference frame theory is used to find the reference source current at fundamental frequency; here extraction of fundamental component from source signal is performed. The control also incorporates the command for maintaining average DC bus voltage of an active filter to a constant value. This method is simple and easy to implement, but do not provide adequate solution under severe conditions of harmonics. Both these methods are unable to suggest control for proper operation of passive filter under transient conditions. The indirect method of taking unit current vectors from the supply and then multiplying them with the output of DC voltage controller provides the reference currents for respective phases. This control approach is simple, low cost and presents acceptable results when compared with p-q theory or SRF control.

Regulation of DC link voltage is another popular method preferred for low and medium power application, which is simple and easy to implement and do not require to sense harmonics and VAR. It ensures effective current control at the source side the harmonic currents are supplied to the nonlinear load.

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multiplied with reference supply current \((i_{rm})\), result in three phase reference supply currents \((i_{sa}, i_{sb}, i_{sc})\). The reference supply currents and sensed supply currents \((i_{sa}, i_{sb}, i_{sc})\) are the inputs for the pulse generator, generating the firing pulses as gating signals to the IGBTs of the hybrid active power filter. The PI controlled hybrid active power filter does not work satisfactorily under load variations; the sliding mode control (SMC) is preferred to regulate the DC bus voltage of HAPF under such conditions. Here sliding mode control is implemented to achieve the desired result.

The sliding mode design approach consists of two components. The first involves the design of a switching function so that the sliding motion satisfies the design specifications. The second is concerned with the selection of a control law, which will make the switching function attractive to the system state.

### A. SLIDING MODE CONTROL

The sliding mode control has been in use with hybrid active power filter for more than one decade. It is preferred over other controllers due to its fastness, robustness and stability under large load variations. The concept behind sliding mode control is defining a surface called sliding surface \(s\), within which the system is controlled in a desired manner. The three basic steps in preparing the SMC model are-

- Proposal of a sliding surface,
- Test of the sliding mode surface existence,
- Control must observe the state of the sliding plane.

The main aim is that when nonlinear load and active power filter are combined, they should present unity power factor load to the supply system.

Sliding mode control is a non-linear method which can control a system even when there is not accurate mathematical model. Certainly, controlling a system with one degree is simpler than a system with \(n\)-degree. Hence, sliding mode control method tries to control an \(n\)-degree system by manipulating its one degree representative system. This system in named as sliding surface.

Sliding mode control is deterministic (only bounds of variations are considered), non-linear (the corrective term is non-linear) and robust (once on the sliding surface, the system is robust to bounded parameters variations and bounded disturbances) due to maintaining the system stability and it performance of the presence in the non ideal parameters. It is applied in the presence of modelling inaccuracies, parameter variations and disturbances, provided that the upper bounds of their absolute values are known. The expected results are confirmed through simulation.

Sliding mode control is a powerful control method that can produce a very robust closed loop system under plant unpredictability and external disturbances, because the sliding mode can be designed entirely independent of these effects. Also, sliding mode controller is inherently stable. This control technique is attractive for the control of non-linear systems because the discontinuous nature of the control action results in outstanding robustness features such as insensitivity to parameter variations and rejection of external disturbances also, the system dynamic involved in a sliding mode control strategy is solely governed by the choice of the switching.

![Fig 3. Sliding Mode Control](image)

From the sliding mode concept the sliding surface or trajectories for the line current can be defined as

\[
i_{refx} = K (v_{sx}) \ldots (3)
\]

Where \(K\) is a constant depending upon the power requirement of the load. Now for the sliding surface \(s\),

\[
s_{x} = [s_{x} - K (v_{sx})] = 0 \ldots (4)
\]

When the state is on the sliding surface, there should be a natural control to satisfy condition.

\[
s \dot{s} < 0 \ldots \ldots (5)
\]

at all instant, for all state conditions.

If the equivalent control to the circuit is such that \(-1 \leq u_{eq} \leq 1\), we observe for the switching action \(u\),

If \(u = -1\) then \(\dot{s} < 0\), at all times i.e. for all values that state may experience.

Here if \(u\) is within natural control bounds of the physical system for \(\dot{s} = 0\), then the system would remain on the sliding surface for all the times.

If \(u\) exceeds the natural bound imposed by sliding surface, the system would be unable to remain on the sliding surface.

From discontinuous control law for the first order system, equation (3) must be satisfied to ensure the switching action driving the state toward the sliding surface.

Also if \(u < u_{eq}\) then \(\dot{s} < 0\), If \(u > u_{eq}\) then \(\dot{s} > 0\). If the equivalent control to the circuit is such that \(-1 \leq u_{eq} \leq 1\), we observe,

If \(u = -1\) then \(\dot{s} < 0\),

If \(u = 1\) then \(\dot{s} > 0\)
We see that if \( s < 0 \), then \( u = 1 \). If \( s > 0 \), then \( u = -1 \) satisfies eqn (3). To apply this control to hybrid active power filter, at each sample time the status of state \( s \) is checked and discontinuous control law is implemented through sliding mode controller.

The main idea is to bring and keep the error on a sliding surface such that the system is insensitive to the disturbances and parameter changes. Sliding mode control is used to regulate voltage of capacitor used in inverter. It improves the dynamic response of the system and provides faster convergence. The performance of SMC is compared with conventional PI controller is good solution for the hybrid active power filter. Because of it is suitable for variation of loads and simple to use in large systems.

B. GENERATION OF UNIT CURRENT VECTOR

The peak amplitude of the supply voltage is derived from sensed three-phase sinusoidal voltages as:

\[
V_{sm} = \left[ \frac{2}{3} (v_{za}^2 + v_{zb}^2 + v_{zc}^2) \right]^{1/2}
\]

(6)

Now the three phase unit vectors can be taken as

\[
u_{za} = \frac{v_{za}}{V_{sm}}, \quad u_{zb} = \frac{v_{zb}}{V_{sm}}, \quad u_{sc} = \frac{v_{sc}}{V_{sm}}
\]

(7)

These unit current vectors, when multiplied with the reference supply current \( I_{sm}^* \), provide with the three phase reference sinusoidal currents in phase with the supply voltage

\[
d_{za}^* = I_{sm}^* \cdot u_{za}, \quad d_{zb}^* = I_{sm}^* \cdot u_{zb}, \quad d_{zc}^* = I_{sm}^* \cdot u_{zc}
\]

(8)

The reference currents when compared with the sensed actual currents provide with the switching signals for the hybrid active power filter.

III. DESIGN OF HYBRID ACTIVE POWER FILTER

A. DESIGN OF PASSIVE FILTER

Passive filters are designed to eliminate the lower order harmonics and to supply the reactive power consumed by the non-linear load. Design of passive filter capacitance is decided by the reactive power requirement, while the inductive reactance is decided by resonance phenomenon for the tuned harmonic frequency [21-22]. For \( n \), harmonic frequency (\( f_n \))

\[
X_{L_n} = h_n \cdot X = \frac{X_{Cn}}{h_n} = X_n
\]

(9)

Where \( h_n \) is the tuning order corresponding to resonant frequency \( f_n = f_0 \). Capacitive reactance of a single tuned filter can be given by-

\[
X_C = \frac{V^2}{Q_C}
\]

(10)

Where \( Q_C \) is the VAr size of the capacitor. And inductive reactance and resistance are given by-

\[
X_L = \frac{X_n}{h_n^2}
\]

\[
R_L = \frac{X}{Q}
\]

(11)

Where \( Q \) is the quality factor of the inductive coil. Size of the passive filter in VAr can be given by-

\[
Q_F = \frac{\frac{V^2}{V_n}}{(X_C - X_L)} = \frac{\frac{V^2}{V_n}}{(X_C - X_L)}
\]

Or

\[
Q_F = \frac{h_n^2}{(h_n^2 - 1)} \cdot \frac{V^2}{X_C} = \frac{h_n^2}{(h_n^2 - 1)} \cdot X_C
\]

(12)

B. DESIGN OF ACTIVE POWER FILTER

A voltage source inverter is used as the active power filter, for which the input DC voltage is essentially constant and independent of the load current drawn [23-24]. A large capacitor is placed across the DC input line to the inverter. The capacitor ensures that any switching event within the inverter do not significantly change the DC input voltage. On the AC side of the VSI, ripple filter is connected, which compensates for the ripples generated in the HAPF current due to fast switching of IGBTs.

SELECTION OF \( L_c, C_{dc}, V_{dc} \)

To keep harmonic distortion in source current within limits, a desirable condition is that the DC bus voltage across the capacitor should rise up to around double the peak source voltage [24]. This choice makes the transient response of the active filter better, as capacitor has sufficient stored energy to meet the requirement of sudden load changes. While deciding rating of DC link capacitor following points are to be considered-

1. Power factor close to unity should be achieved with any type of load,
2. A constant DC voltage should be maintained across the capacitor with minimum ripples,
3. Steady state as well as transient response must be fast.

The DC bus capacitance of the HAPF system can be calculated from the energy requirement of the capacitor [23]-

\[
\Delta e_{dc} = \frac{1}{2} C_{dc} [(V_{dc})^2 - (V_{dc})^2]
\]

(13)
Here \( \Delta e_{dc} \) is the energy required by the capacitor to be stored for keeping the DC bus voltage near reference value. Design of filter inductance \((R_c, L_c)\) depends upon the switching frequency of the hysteresis band current controller. The HAPF circuit shown in Fig.1 can be represented by equation

\[
R_c + L_c \frac{d}{dt}v_c = v_s
\]  
(14)

where \( v_c \) is the voltage at the VSI-midpoint. Average value of \( v_c \) is assumed equal to the addition of voltage \( v_s \) and voltage drop across ripple filter \((L_c, R_c)\). Voltage drop across inductor of the ripple filter is considered to be around 10% of the supply voltage, drop across resistance \( R_c \) is very small compared to that across \( L_c \) and therefore can be neglected.

Thus the equation (15) becomes

\[
L_c \frac{d}{dt}v_c = -v_c + v_s = -1.1V_{sm} + V_{sm}
\]  
(15)

Lower value of ripple filter inductance is selected for taking into account the variation in switching frequency. Hysteresis bandwidth of controller is taken as \( \pm 0.2 \). Calculated values of \( C_{dc}, V_{dc} \) and \( L_c \) and nearer values are implemented on the system and system performance judged on parameters like power factor, transient response and %THD. The calculated system parameters are: \( C_{dc}=2200\mu F, V_{dc}= 45V \) and \( L_c=3.35mH \).

C. SELECTION OF SMC PARAMETERS

Sliding mode control can be defined as a means to maintain the system within a surface called sliding surface and hence obtaining a desired system output. In sliding mode controller the peak value of supply current is calculated with the help of DC link capacitor voltage \( V_c \) and the reference voltage \( V_{dc} \). The error \( v_e \) at any instant is defined as-

\[
v_e(t) = V_{dc}^*(t) - V_{dc}(t) = x_1
\]  
(16)

And its derivative at that instant is defined as-

\[
x_2 = x_1 = [v_e(t)-v_e(t-1)]
\]  
(17)

Where \( x_1 \) and \( x_2 \) are the state variables.

In sliding surface, the switching functions \( y_1 \) and \( y_2 \) are given by

\[
y_1 = +1 \text{ if } zx_1 > 0 \\
y_1 = -1 \text{ if } zx_1 < 0 \\
y_2 = +1 \text{ if } zx_2 > 0 \\
y_2 = -1 \text{ if } zx_2 < 0
\]  
(18)

Where \( z=c_1x_1+c_2x_2 \) is the switching variable for the sliding surface.

Now the output of the SMC can be calculated as peak supply current \( I_{sm} \) as-

\[
U(t) = c_1x_1y_1 + c_2x_2y_2 = I_{sm}^*
\]  
(19)

Where \( c_1, c_2, c_3, c_4 \) are the constants of sliding mode controller. The controller parameters must be positive to assure the existence condition of the sliding mode and to have a good behaviour of the controlled system. Based on above calculation empirical values of sliding mode controller parameters and respective changes in THD are calculated.

IV. MATLAB Simulation Results

Simulation results of this paper are as shown in below Figs.5 to 8.

Fig.5: (a) source voltage, (b) source current (c) load current when HAFU in OFF Mode.
V. Power Quality Improvement

It is observed that the source current on the grid is affected due to the effects of nonlinear load, thus purity of waveform may be lost on both sides in the system. The inverter output voltage under HAFU operation with load variation is shown in Fig. 6. The dynamic load does affect the inverter output voltage. The source current with and without HAFU operation is shown in Fig. 5. This shows that the unity power factor is maintained for the source power when the HAFU is in operation. The current waveform before and after the HAFU operation is analyzed. The Fourier analysis of this waveform is expressed and the THD of this source current at PCC without HAFU is 12.65%, as shown in Fig. 7. The power quality improvement is observed at point of common coupling, when the controller is in ON condition. The THD of the source current with HAFU is 3.60%, as shown in Fig. 8.

VI. CONCLUSION

This paper presents a hybrid active filter to suppress harmonic resonances in industrial power systems. The proposed hybrid filter is composed of a lower order harmonic-tuned passive filter and an active filter in series connection at the secondary side of the distribution transformer. With the active filter part operating as variable harmonic conductance, the filtering performances of the passive filter can be significantly improved. Accordingly, the harmonic resonances can be avoided, and the harmonic distortion can be maintained inside an acceptable level in case of load changes and variations of line impedance of the power system.

Experimental results verify the effectiveness of the proposed method. Extended discussions are summarized as follows.

- Large line inductance and large nonlinear load may result in severe voltage distortion. The conductance is increased to maintain distortion to an acceptable level.
- Line resistance may help reduce voltage distortion. The conductance is decreased accordingly.
• For low line impedance, THD should be reduced to enhance filtering performances. In this situation, measuring voltage distortion becomes a challenging issue.
• High-frequency resonances resulting from capacitive filters are possible to be suppressed by the proposed method.
• In case of unbalanced voltage, a band-rejected filter is needed to filter out second-order harmonics if the SRF is realized to extract voltage harmonics.

VI. REFERENCES

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