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A First Order Sliding Mode Controller for Grid Connected Shunt Active Filter with a LCL Filter

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Abstract: A first order sliding mode controller with appropriate parameters sliding surface (modeled in usual time domain and realized by transfer function) is considered here for LCL grid connected three phases three wires shunt active filter (SAF). If shunt active conditioners are already well known in compensation for the main types of current disturbances in the electrical power systems, it is also admitted that they generate some undesired components caused by VSI switching frequency. In order to prevent these components from spreading to the grid side, a LCL output filter is generally proposed. In this context, a VSI connected grid via a LCL filter is largely proposed for renewable energy systems, where the component to be injected into the grid is only the fundamental. Unfortunately, when the injected components include fundamental plus harmonics and for a LCL output filter associated to linear controllers, a phase shift appears, between the identified harmonics current and the injected current. This phase shift impacts negatively the current disturbances filtration and/or compensation of the SAF. Therefore, sliding mode controller with appropriate sliding surface, in both time and frequency domains, is proposed as nonlinear control method, to overcome the phase shift effects over the entire bandwidth, for the shunt active filter. Besides, a PWM-SM-Controller, with zero order hold in input of the PWM, will allow to operate in a fixed frequency, preventing a variable switching frequency effects. The rapidity, tracking and robustness of this proposed controller, within the SAF, are validated by Matlab, Simulink, Simscap-Sim_Power_System code.

Keywords: Shunt Active Filter, Sliding mode control, LCL output filter, chattering effects, harmonics, Phase shift, RST controller.

INTRODUCTION

The electric systems and machines of the modern world, depend more and more of the power electronics, to operate effectively and sustainably. Without this technology, the electric motors will still work at full speed, renewable energy, both solar and wind, could not supply the electric network. Similarly, harmonics would disturb the distribution networks. Voltage source inverters (VSI) are used for energy conversion from a DC source to an AC output, either in a standalone mode or when connected to the utility grid. A filter is required between a VSI and the grid, reducing harmonics of the output current and imposing a current-like performance for feedback control. A simple series inductor (first order output filter) can be used [Stefanutti (2006)], but the attenuation of high frequency components, due to switching frequency, is not very pronounced. In addition, a high voltage drop is produced and the inductor, required in the design, is very bulky [Bouchafa (2010)]. Commonly a high-order output LCL filter (called also T-filter) has been used in place of the conventional L-filter, for smoothing the high frequency output currents from a VSI [Bouchafa (2010)]. Indeed, LCL filter provides, in comparison with the first order one, higher attenuation of high frequency components as well as cost savings, in term of the overall weight reduction and the size of the components.

In this context, a grid connected VSI with LCL filter is mainly proposed for the renewable energy (photovoltaic and wind) systems [Wang (2011)]. The grid-connected VSIs have, in this case, to inject only fundamental components to the grid. On the other hand, shunt active conditioners are becoming, in most industrial countries, an alternative solution to compensate for all current disturbances in electrical installations, such as harmonic, unbalance and reactive currents. In this case, current control loop, of the shunt active conditioner, has to ensure a good compensating performance over the entire bandwidth harmonic frequencies, including the fundamental. For this purpose, a PWM-VSI with an adapted linear controller (such as RST: Robust Roots Locus) is proposed [Alali (2002), (2004)]. However, this controller cannot guarantee good compensation. Indeed, although the tracking of the magnitude of identified disturbances currents was quite good, a phase shift between the reference and the injected currents appears in the current control loop, degrading the compensation performance and limiting consequently the integration of the LCL filters in the structure of the shunt active conditioners [Alali (2004)]. In order to overcome the phase lag effects over the entire bandwidth for LCL grid connected shunt active conditioner, an advanced RST controller is proposed, called RSTimp [Alali (2004)]. Despite the fact that the high compensating performance ensured by this improved method in the continuous domain, this method is largely limited in the discrete domain [Alali (2002)]. Indeed, Shannon theory, Nyquest
frequency and other constraints, imply very high switching and sampling frequencies, which are still limited by VSI power rating components and costs.

To overcome these problems, two different methodological ways are proposed: a technological path and nonlinear control path. The technological path consists of increasing sufficiently the inverter switching frequency, by changing the traditional structure of the VSI, while maintaining a first order output filter (with minimal of constraints), associated to a simple linear controller or a conventional nonlinear one. This goal is achieved (sufficiently increasing the switching frequency), using two different structures as, Multicell Series Inverter [Salinas (2015)] and Three-level Neutral Point Clamped (NPC) topology circuit [Sebaaly (2014)].

The control path opts to keep a conventional structure of the VSI (two levels system configuration), while using an output LCL filter (easy to implement), along with an adapted nonlinear controller, such as sliding mode controller.

It is important to mention that some compensation methodologies have proposed to build sinusoidal consumption loads [Itoh (2000), Doria (2016)]. However, these solutions involve additional costs for each elements and do not solve the problems caused by all the polluting loads that already exist on the market. Other control methods propose to control the injected current of the VSI in the dq rotating reference frame, but unfortunately without the presence of harmonics [Pogaku (2007)].

In this research, a first order sliding mode controller with an appropriate sliding surface is proposed, in both time and frequency domains. In this case, LCL grid connected shunt active conditioner become universal, by compensating all current disturbances as reactive, unbalance and harmonic currents.

**SHUNT ACTIVE CONDITIONER STRUCTURE**

**General basic structure**

In the distribution electrical power systems, most power quality problems are associated with voltage harmonics, unbalanced voltages and reactive power. These disturbances are usually generated by unbalanced and inductive consumption and by non-linear loads. Therefore, shunt active filters are generally proposed to cancel the current disturbances and subsequently reducing the voltage disturbances of the same nature [Alali (2004)].

**Output current control loop**

A PWM three-phase voltage source inverter (VSI) is used to generate the current to be injected to the network supply. The VSI is connected to the electrical network via a passive output filter. The output filter must be designed to block the components of the switching frequency, generated by the PWM-VSI.

**2.2.1 Transfer function and state space models of the LCL output filter**

A single phase equivalent circuit of the LCL output filter is shown in Fig.2.

![Fig. 2 A single phase model of LCL output filter](image)

The LCL filter is modelled by the following s domain equations [Alali (2004)]:

\[
I_{\text{inf}}(s) = \frac{B_1(s)}{A(s)} V_f(s) + \frac{B_2(s)}{A(s)} V_i(s)
\]

\[
A(s) = a_1 s^3 + a_2 s^2 + a_3 s
\]

\[
b_1(s) = b_{11} s^3 + b_{12}
\]

\[
b_2(s) = -(b_{21} s^3 + b_{22} s + b_{23})
\]

\[
a_1 = (L_s + L_{f2}) L_{f1} C_f
\]

\[
a_2 = [(L_s + L_{f2}) R_{f1} C_f + (R_s + R_{f2}) L_{f1} C_f + (R_{f1} + R_s + R_{f2}) R_{f1} C_f]
\]

\[
a_3 = [(L_s + L_{f2}) + L_{f1} + (R_s + R_{f2}) R_{f1} C_f + (R_{f1} + R_s + R_{f2}) R_{f1} C_f]
\]

\[
a_4 = R_{f1} + R_s + R_{f2}
\]

\[
b_{11} = R_{f1} C_f
\]

\[
b_{12} = 1
\]

\[
b_{21} = L_{f1} C_f
\]

\[
b_{22} = (R_{f1} + R_{f1}) C_f
\]

\[
b_{23} = 1
\]

Where \(L_s\) is the inverter side inductor, \(L_{f2}\) is the grid-side inductor, \(C_f\) is a capacitor with a series \(R_f\) damping resistor, \(R_s\) and \(R_{f2}\) are inductors resistances, \(L_s\) and \(R_f\) are grid inductor and resistor respectively. 

\(B_1(s)/A(s)\) is the transfer function model of the LCL filter and \(B_2(s)/A(s)\) represents a disturbance model. \(V_i(s)\) is the inverter output voltage and \(V_f(s)\) is the PCC network voltage, which is considered as a disturbance. Currents \(I_r, I_s, I_{\text{inf}}\) are inverter output current, capacitor current, and grid injected current, respectively and \(V_c\) is capacitor voltage.
If we neglect all resistances (excepted the damping one), the transfer function of the LCL filter will be:

$$B(s) = \frac{(C_f R_f) s + 1}{A(s) (L_{f1} L_{f2} C_f) s^3 + C_f R_f (L_{f1} + L_{f2}) s^2 + (L_{f1} + L_{f2}) s}$$

Now, for industrial applications, $R_f$ should be zero, then the cut-off frequency of the T filter is:

$$f_{cp} = \frac{1}{2\pi \sqrt{\frac{L_{f1} L_{f2}}{L_{f1} + L_{f2}}}}$$

The state space model of the same single phase LCL output filter is [Reznik (2014)]:

$$\begin{bmatrix}
\frac{dv_f}{dt} \\
\frac{di_f}{dt} \\
\frac{di_{inj}}{dt}
\end{bmatrix} = \begin{bmatrix}
\frac{R_f + R_f}{L_{f1}} & \frac{R_f}{L_{f1}} & -\frac{1}{L_{f1}} \\
\frac{L_{f2}}{L_{f2}} & \frac{R_f + R_f}{L_{f2}} & -\frac{1}{L_{f2}} \\
-C_f & -C_f & 0
\end{bmatrix} \begin{bmatrix} i_f \\ i_{inj} \\ v_f \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} v_s$$

The equations show no cross-coupling terms as indicated by the matrix expression:

$$\frac{dv_c}{dt} = i_f - i_{inj}$$

$$\frac{di_f}{dt} = \frac{1}{L_{f1}} (v_{inv} - v_c - R_f (i_f - i_{inj}) - R_f i_f)$$

$$\frac{di_{inj}}{dt} = \frac{1}{L_{f2}} (v_c + R_f (i_f - i_{inj}) - v_s - R_f i_{inj})$$

CONTROL METHODS

Linear control Algorithm

The control strategy is based on, detecting the current disturbances (current reference $I_{ref}$) by means of an identification method, and then to drive the VSI by a PWM technology, in order to generate these references as injected currents ($I_{inj}$) in the grid.

Fig. 3 General block scheme of current control algorithm

To insure a good tracking between $I_{ref}$ and $I_{inj}$, the control strategy integrates a current control loop. Fig. 3 shows a general block scheme of the current control algorithm. In this scheme, a LCL grid connected PWM-VSI with a robust roots locus (RST) controller and an instantaneous power method, for current disturbances identification are proposed [Akagi (1996), Alali (2004)]. The voltage network $V_s$ represents here external disturbance, whose effects are compensated by adding the same network voltage to the control signal ($u$). This will prevent the fundamental current from passing from the network to the active conditioner [Alali (2002)].

3.2 Phase shift effect problems

The RST control method, as all linear controllers, are generally used when the reference to be tracked is either a constant or a single low frequency signal. In the low single-frequency case (i.e. unbalance or reactive power compensation), phase lag between reference ($I_{ref}$) and injected ($I_{inj}$) signals is acceptable. However, the phase lag is unacceptable when the reference signal includes multiple frequencies, as phase lag increases with frequency. Moreover, higher the order of the controlled system (output filter here), the higher the phase lag is. Fig. 4 illustrates the phase lag effect for the structure presented in Fig. 3. From fig. 4, it is simple to noticed that the distorted current ($I_{load}$), is not correctly compensated for ($I_{ideal}$: compensation with phase shift), compared to the ideal form ($I_{ideal}$: compensation without phase shift).
frequency, a phase lag of (-1) is negligible. Beyond this, phase lag
is no longer negligible and the shunt active conditioner cannot
compensate for current harmonics.

For all above reasons, nonlinear control seems unavoidable in
to dominate all the frequency harmonic spectrum in closed
loop, linear controller of higher order was proposed.

The main control researches made for grid connected VSI with
LCL filter, were originally established for the renewable energy
(photo voltaic and wind) systems [Wang (2011)]. The control of
these VSIs must achieve high performance in the sense of fast
dynamic response, robustness to perturbations, none tracking
error, and low total harmonic distortion [Meza (2012)].

Unfortunately, and as previously explained, phase shift problem is
more pronounced with both higher order controller and large
frequency controlled spectrum [Alali (2004)].

For all above reasons, nonlinear control seems unavoidable in
order to respond to all control requirements. In this context and as
an alternative solution of linear control, this research proposes
nonlinear sliding-mode control (SMC) strategy. The nonlinear
SMC ensures good dynamic response, strong robustness, and
good regulation properties in a wide range of operating conditions
[Jung (1996)]. This control design leads to a sliding surface, which
is a linear combination of the system-state variables and the
generated references. However, the sliding mode controllers, as
they were proposed, are affected by the drawback of a variable
switching frequency. This can lead to possible resonance, if the
switching frequency match the natural frequency of the LCL
output filter.

In this research and for universal shunt active filter design
purposes, a PWM-VSI is proposed to ensures sliding mode
controller to operate at fixed frequency, preventing variable
switching frequency effects. This fixed frequency is due to the fact
that the input of the PWM is a ZOH at the switching frequency.
Besides, a first order sliding mode controller, in both time and
frequency domains, is presented. Finally, the sliding surface of the
SMC will be chosen carefully, according to the third order output
T-filter.

Sliding mode controller calculation

Considering the system in state space representation with
y := i_{eq} as output, u := v_r as input and w := v_i as disturbances and
R_i := 0, equation (1) becomes:

\[
\frac{dX}{dt} = AX + Bu + Pw
\]

y = CX, \quad C = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}

With \( X = \begin{bmatrix} \frac{di_f}{dt} & \frac{di_{inj}}{dt} & \frac{dv_s}{dt} \end{bmatrix}^T \) and:

\[
A = \begin{bmatrix}
\frac{-R_1}{L_f} & 0 & \frac{-1}{L_f} \\
0 & \frac{-R_2}{L_f} & \frac{1}{L_f} \\
\frac{1}{C_f} & 0 & \frac{1}{C_f}
\end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \quad P = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}
\]

From (2), it is obvious that the relative degree of the system is
equal to two (CB=1AB=0 and CA\beta=1/(1/L_2C_1)) and that the
matching condition [Drazenovic (1969)] is not verified
CP1/L_2, but as the perturbation is at least \( C_2 \), with
\( v_r, \frac{dv_r}{dt}, \frac{d^2v_r}{dt^2} \) bounded, then a sliding manifold of the form

\[
S = K_0(v_{inj} - i_{ref}) + K_1 \left( \frac{di_{inj}}{dt} - \frac{di_{ref}}{dt} \right) + K_2 \left( \frac{d^2i_{inj}}{dt^2} - \frac{d^2i_{ref}}{dt^2} \right)
\]

can be chosen. (3) is such that dS/dt is function of the input \( v_i \),
moreover the terms \( K_0, K_1 \) and \( K_2 \) are chosen such that (3) is
exponentially stable. More precisely, the choice of the Ki is such
that the pole placement was not too fast, because, the effect of the
disturbance on dS/dt is equal to

\[
-K_0 \left( \frac{R_1}{L_f} + \frac{1}{L_fC_f} \right) v_i + \frac{R_2}{L_f} \frac{dv_r}{dt} + \frac{1}{L_f} \frac{d^2v_r}{dt^2} - K_0 \frac{1}{L_f} v_i +
\]

and also, designed in order that the averaging assumption with
respect to the PWM was verified. But, must be sufficiently fast in
order that \( i_{inj} \) converges sufficiently fast to \( i_{ref} \), because for a time
computational constraint, a first order sliding mode control is

\[
-K_0 \frac{1}{L_f} \frac{dv_r}{dt} + \frac{R_2}{L_f} \frac{d^2v_r}{dt^2}
\]

Considering the system in state space representation with
y := i_{eq} as output, u := v_r as input and w := v_i as disturbances and
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0 & \frac{-R_2}{L_f} & \frac{1}{L_f} \\
\frac{1}{C_f} & 0 & \frac{1}{C_f}
\end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \quad P = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}
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CP1/L_2, but as the perturbation is at least \( C_2 \), with
\( v_r, \frac{dv_r}{dt}, \frac{d^2v_r}{dt^2} \) bounded, then a sliding manifold of the form

\[
S = K_0(v_{inj} - i_{ref}) + K_1 \left( \frac{di_{inj}}{dt} - \frac{di_{ref}}{dt} \right) + K_2 \left( \frac{d^2i_{inj}}{dt^2} - \frac{d^2i_{ref}}{dt^2} \right)
\]

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moreover the terms \( K_0, K_1 \) and \( K_2 \) are chosen such that (3) is
exponentially stable. More precisely, the choice of the Ki is such
that the pole placement was not too fast, because, the effect of the
disturbance on dS/dt is equal to

\[
-K_0 \left( \frac{R_1}{L_f} + \frac{1}{L_fC_f} \right) v_i + \frac{R_2}{L_f} \frac{dv_r}{dt} + \frac{1}{L_f} \frac{d^2v_r}{dt^2} - K_0 \frac{1}{L_f} v_i +
\]

and also, designed in order that the averaging assumption with
respect to the PWM was verified. But, must be sufficiently fast in
order that \( i_{inj} \) converges sufficiently fast to \( i_{ref} \), because for a time
computational constraint, a first order sliding mode control is

\[
-K_0 \frac{1}{L_f} \frac{dv_r}{dt} + \frac{R_2}{L_f} \frac{d^2v_r}{dt^2}
\]
design without correcting equivalent vector control term [Utkin (1992)]. Then the control as the following simple form:

\[ u = -\dot{\lambda} \text{sign}(S) \]  

(5)

Where \( \dot{\lambda} \) is fixed by the saturation limiter block to 420V (see Fig. 3), then the action of the control on \( \frac{dS}{dt} \) is proportional to \( K_2 \) and this explain the choice of the \( K_0 \) and \( K_1 \) with respect to (4).

**SIMULATION RESULTS**

In this work, the network is made up of a sub-transformer 20/0.4 kV, 1 MVA, ucc=4%, supplied by a network whose short-circuit power is Ssc=500 MVA. The non-linear load is a 100 kVA six-pulse thyristor rectifier with R/C load. The harmonics filtration performance of the shunt active filter is tested, to eliminate the harmonics generated by the nonlinear load, using Matlab, Simulink, Simscap-Sim_Power_System. In these simulations, the shunt active filter has a T-type output filter while the injected current is controlled by the SM-Controller, modeled in usual time domain and realized by transfer function. The sign function is approximated, for computation reason, by a hysteresis function, with very small band (10^{-16}). Additionally, a PI controller is implemented to regulate the direct voltage storage capacitor \( V_{dc} \).

The system rating values, considered in the general structure, are given in Table 2.

| Table 2: Electrical network characteristics |
|---------------------------------------------|
| **Shunt Active Filter**                     |
| Electrical Network                         |
| Ssc=500 MVA, 20kV, Transfo: 1 MVA, 20/0.4 kV ucc=4% |
| Rs=0.25 mΩ, Ls=19.4 µH                       |
| Output LCL filter                           |
| Lf1=90 µH, Rf1= 5 mΩ                        |
| Lf2=100 µH, Rf2= 5 mΩ                       |
| Cf= 130 µF, Rf= 0 Ω                         |
| Storage capacity                            |
| C= 130 µF, Vdc=840 V                        |
| LCL Cut-off frequency                       |
| 2000 Hz                                     |
| Switching Frequency                         |
| 16 kHz                                      |

**4.1 SM-Controller transfer function based simulation**

The Fig.6 shows simulation results of the shunt active filter, connected to a disturbed electric grid via LCL filter and controlled by a first order sliding mode controller, modeled in frequency domain.

The active filter is cutted-off after 5 operating periods (\( \approx 0.1 \) s). This figure shows the results of network currents \( (I_s) \) after and before compensation, the identified current harmonic \( I_{ref} \) and the injected current to the network \( I_{inj} \), for phase1, superimposed and the total harmonic distortion of current \( (THD-I_s) \) at network side, after and before compensation. From Fig. 6, we remark that, despite the presence of the LCL filter, there is no phase lag between the current reference and the injected current, with a very fast tracking. Thus, the source line current pattern is good, without any presence of high frequency components at the network side.

This is reflected on the same Fig.6, by an important decrease of current \( (THD-I_s) \), of the phase 1, from about 24% before compensation to less than 1% after compensation, for the network side, which explains the almost pure sinusoidal current, at the network side, after the filtration.

The same observation can be noticed for the network voltage, on the Fig.7. Indeed, a voltage \( (THD-v) \) of 0.45%, after filtering, at grid side is almost negligible.

**CONCLUSIONS**

It is clear that the conventional structure of a VSI (two levels voltage configuration), connected to the grid via a LCL output filter, becomes universal, if we succeed to assign it to an appropriate nonlinear sliding mode controller. Indeed, if this controller is able to ensure accurate and fast tracking for both fundamental and harmonics components, the VSI and...
consequently the shunt active filter becomes a universal solution for all current disturbances compensation. In this context, this research has taken benefit of a LCL output filter, compared with a simple series inductor, to ensure that the switching frequency has been filtered out of the injected signal. However, such compensation conditions require a specific linear controller of higher order. However, a phase lag between reference ($I_{ref}$) and injected ($I_{inj}$) signals appears, preventing a good harmonic filtering, as it increases with frequency. Moreover, higher the order of the controlled system (LCL filter), the higher the phase lag is. To overcome phase shift limitation, while ensuring dynamic response, strong robustness and good regulation properties in a wide range of operating conditions, this research has proposed a sliding mode method of first order, with a judicious choice of the sliding surface. Besides, we were able to model this sliding mode controller, in both time and frequency domains, using differential equations and transfer function respectively. Modeling this controller as a transfer function would make, subsequently, the implementation of the control-command part of the VSI much easier. In addition, the association of a PWM control technology, with zero order hold in input of the PWM, has allowed to the SMC to operate in a fixed frequency, preventing a variable switching frequency effects, as a possible resonance with the natural frequency of the LCL filter or converter damage.

Finally, the simulations, performed in Matlab, Simulink, Simscape-SimPower-System, have proved that the proposed nonlinear controller, for its both time and frequency models, meet the objective of good, fast and robust tracking and consequently realizing a universal shunt active filter.

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