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Flatness of the Three-Phase Grid Connected DC-AC Inverter with LCL Filter*

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Abstract. The three-phase inverter, connected to the grid by an LCL filter, is vulnerable to multiple faults, therefore an active fault-tolerant control is required to preserve the electrical power conversion between renewable resources and the grid. In this work, we provide a flatness analysis of the inverter and its LCL filter, the goal being to determine whether the flatness-based control structure stays accurate under both healthy and faulty circumstances.

Keywords: DC-AC inverter · Grid · Flatness analysis · Fault control.

1 Introduction

The paper investigates the flatness of the three-phase grid connected inverter under healthy and faulty modes operation, in the framework of distributed power generation systems (DGPS). Numerous defects, such as excessive or low DC voltage compared to the healthy constant value, Mosfet faults, and grid-side faults can cause the grid-connected inverter to fail completely and shut down the DGPS [1, 11, 12, 14, 16]. In this paper, we consider only the fault related to the incorrect closure of the Mosfet [3], the goal being to preserve the electrical power conversion between the renewable sources and the grid. To achieve this, a fault detection technique associated with a real-time active fault tolerant control is proposed. The problems of fault detection, localization and estimation are not covered in this

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paper. In this contribution, we model the faulty system in the abc frame, that does not consider the system balanced compared to the dq frame. Even if the homopolar component of the unbalanced system is included in the $dq0$ frame, see [5, 19], this control does not localize the faults. The proposed active fault control is based on the differential flatness [9, 13] of the considered model, which allows all system states and controls to be parameterized as functions of the flat output and a finite number of its time-derivatives. There are various benefits of this control, such as a simple trajectory tracking [20] and the absence of zero dynamics [8]. Moreover, in the present study case, the structure of the flatness-based control is the same for both systems with or without faults compared to the other existing controls [4, 6, 7, 17, 18]. For example the PI controller has to adjust their gains during the occurred faults. From this last point of view, a general model that works for both healthy and faulty conditions of the three-phase grid connected inverter is proposed. The healthy and faulty models are both designed with respect to losses characterization and estimation. The difference between the models is only that the losses level is higher for the faulty model. Then it is demonstrated that a chosen flat output of the healthy model is also relevant for the faulty model.

The remaining paper is organised as follows: The flatness analysis of the considered system is given in Section 2. The simulation results are presented in Section 3. In Section 4, conclusions and perspectives are discussed.

The main notations used in this paper are given in Table 1.

Table 1. Paper nomenclature

Acronyms	Meaning	Acronyms	Meaning
V_{dc}	DC bus voltage (constant)	R_{on}	Conduction resistance of the Mosfet
i_{dc}	DC current	$\Delta v_{jl}, \Delta r_{jl}$	Losses related to the low Mosfet
j	phase index, $j \in \{a, b, c\}$	$\Delta v_{jh}, \Delta r_{jh}$	Losses related to the high Mosfet
i_j	Inverter output current	L_1	Inverter output inductance
v_{fj}	Capacitor voltage	r_1	Internal resistor of L_1
i_{gj}	Grid current	L_2	Grid side inductance
v_{gj}	Grid voltage	r_2	Internal resistor of L_2
K_j	Switch state	C_f	Filter Capacitor
f_{sw}	Switching frequency	R_d	Damping resistor
f_g	Grid frequency	f_g	Grid frequency
α_j	Average control ($\alpha_j \in (0, 1)$)	i_s, i_s'	Homopolar currents
P	Active power of the system	φ	Flat output

2 Flatness of the three-phase grid connected inverter with LCL filter: faulty model

The considered model is a model that uses the losses to detect the fault, this model is presented in Fig. 1. The averaged equations of this model are presented in Section 2.1, which are suitable to analyze its flatness, see Section 2.2, (we work with the continuous-time averaged model instead of the switching model because the flatness theory for switching systems is more involved). The losses

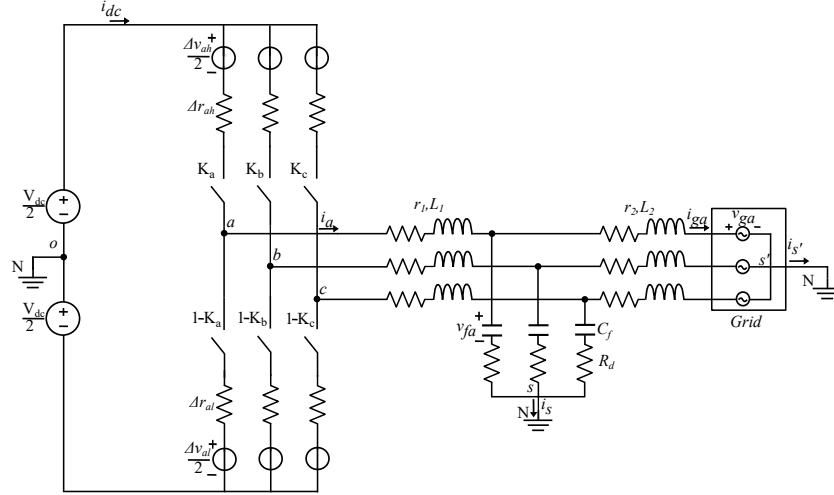


Fig. 1. Model of the three-phase grid connected inverter with LCL filter.

$\Delta v_{jh}, \Delta r_{jh}, \Delta v_{jl}, \Delta r_{jl}$, are supposed known. The healthy model of Fig. 1 is obtained with the condition that $\Delta v_{jh} = \Delta v_{jl}$ and $\Delta r_{jh} = \Delta r_{jl}$. The proposed model works for both healthy and faulty circumstances. As mentioned in the introduction, the fault considered in this paper is an inappropriately closed Mosfet. As an example, the ill component is supposed to be at the low Mosfet of the phase a . The fault is detected when the resistance Δr_{al} and the voltage drop Δv_{al} are high compared to the healthy levels.

2.1 The average model

The average model of phase a is described by:

$$\begin{bmatrix} \frac{d\bar{i}_a}{dt} \\ \frac{d\bar{i}_{ga}}{dt} \\ \frac{d\bar{v}_{fa}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{r_1+R_d+\Delta r_{al}}{L_1}\bar{i}_a + \frac{R_d}{L_1}\bar{i}_{ga} - \frac{1}{L_1}\bar{v}_{fa} \\ -\frac{V_{dc}-\Delta v_{al}}{2L_1} \\ \frac{R_d}{L_2}\bar{i}_a - \frac{r_2+R_d}{L_2}\bar{i}_{ga} + \frac{1}{L_2}\bar{v}_{fa} - \frac{1}{L_2}v_{ga} \\ \frac{1}{C_f}\bar{i}_a - \frac{1}{C_f}\bar{i}_{ga} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \left(-(\Delta r_{ah} - \Delta r_{al})\bar{i}_a \right) \\ -\frac{\Delta v_{ah}}{2} - \frac{\Delta v_{al}}{2} + V_{dc} \\ 0 \\ 0 \end{bmatrix} \alpha_a, \quad (1)$$

and is of the form

$$\dot{x}_a = f(x_a) + g(x_a)u_a, \quad (2)$$

with $x_a = [\bar{i}_a, \bar{i}_{ga}, \bar{v}_{fa}]^T \in \mathbb{R}^3$ and $u_a = \alpha_a \in (0, 1)$. Model (1) is a non-linear control-affine system.

The average model of the three-phase grid connected inverter consists of three identical and decoupled subsystems of the form (1) (one subsystem for each phase). The focus is made on phase a and the results can be expanded to other phases.

From now on, by faulty model we understand model (1) for which $\Delta v_{ah} \neq \Delta v_{al}$ and $\Delta r_{ah} \neq \Delta r_{al}$ (the losses level is higher for the faulty model), while for the healthy model, we will always have $\Delta v_{ah} = \Delta v_{al}$ and $\Delta r_{ah} = \Delta r_{al}$.

Remark 1. The approach that we employ in this work can also handle symmetrical faults (where both the high and low Mosfets are damaged). We only focus on asymmetrical faults because they are more probable to appear.

2.2 Flatness study of the average model

Definition 1 (Flatness [9]). *The system $\Xi : \dot{x} = F(x, u)$, where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^m$ is flat, if there locally exist m smooth functions $\varphi_k(x, u, \dots, u^{(l)})$, for $1 \leq k \leq m$, such that locally*

$$x = \gamma(\varphi, \dots, \varphi^{(\beta-1)}) \text{ and } u = \psi(\varphi, \dots, \varphi^{(\beta)}),$$

for a certain integer β , where $\varphi = (\varphi_1, \dots, \varphi_m)$ is called a flat output.

Proposition 1. *The following conditions hold:*

- (i) *The healthy system, given by (1), with $\Delta v_{ah} = \Delta v_{al}$ and $\Delta r_{ah} = \Delta r_{al}$, is flat with $\varphi = \bar{i}_{ga} - \frac{R_d C_f}{L_2} \bar{v}_{fa}$ being a flat output.*

(ii) The faulty system, given by (1) and for which we suppose that

$$-0.5\Delta v_{ah} - 0.5\Delta v_{al} + V_{dc} + (\Delta r_{al} - \Delta r_{ah})\bar{i}_a \neq 0, \quad (3)$$

is flat with $\varphi = \bar{i}_{ga} - \frac{R_d C_f}{L_2} \bar{v}_{fa}$ being a flat output.

Notice that since (1) is a single-input control system, the flat output φ has only one component.

Proof. The proof of (i) follows the same line as that of condition (ii) that is given below.

Proof of (ii). Let us consider the faulty model given by (1). A necessary condition for φ to be a flat output of (1) is that the matrix $G = [g, ad_f(g), ad_f^2(g)]$ is invertible, see [20], where $ad_f g = [f, g]$ is the Lie Bracket [10] of the vector fields f and g describing the dynamics of (1) (recall that we rewrote system (1) into the compact form (2)), and $ad_f^2(g) = [f, ad_f(g)]$. By a straightforward computation it can be shown that the rank of the 3×3 - matrix G is three if condition (3) is satisfied.

The function $\varphi = \bar{i}_{ga} - \frac{R_d C_f}{L_2} \bar{v}_{fa}$ is a flat output if the following conditions are satisfied

$$\begin{cases} \mathcal{L}_g \varphi = 0 \\ \mathcal{L}_g \mathcal{L}_f \varphi = 0 \\ \mathcal{L}_g \mathcal{L}_f^2 \varphi \neq 0 \end{cases},$$

where $\mathcal{L}_g \varphi$ is the Lie derivative φ along the vector field g [10], which can be easily verified by a direct calculation. \square

Assumption 1. From now on, we assume that the fault Δr_{al} is always such that (3) is satisfied (that is, we avoid the flatness singularity).

Assumption 1 guarantees that φ is a flat output for both the healthy and faulty models. Thus the same flatness-based control in both healthy and unhealthy circumstances is applied according to Proposition 1 and Assumption 1. The expression of u_a as function of $\varphi^{(3)}$ is: $u_a = \frac{1}{\mathcal{L}_g \mathcal{L}_f^2 \varphi} (\varphi^{(3)} - \mathcal{L}_f^3 \varphi)$.

The feedback $v_a = \mathcal{L}_f^3 \varphi + \mathcal{L}_g \mathcal{L}_f^2 \varphi u_a$, is applied to get $\varphi^{(3)} = v_a$ and only then the following feedback controller [10] is used for tracking the flat output reference φ^* :

$$v_a = -K_1(\varphi - \varphi^*) - K_2(\dot{\varphi} - \dot{\varphi}^*) - K_3(\ddot{\varphi} - \ddot{\varphi}^*) + \varphi^{*(3)}, \quad (4)$$

where K_1, K_2, K_3 are the gains of the feedback controller (they are chosen such that the feedback controller is stable).

Remark 2. Due to the fact that both the healthy and faulty models admit the same flat output φ (and will thus have the same reference trajectory φ^*), the feedback controller (4) is unaffected by healthy or unhealthy conditions. On the other hand, observe that the control u_a is dependent on the fault value through the terms $\mathcal{L}_f^3\varphi$ and $\mathcal{L}_g\mathcal{L}_f^2\varphi$.

3 Simulation Results

The Ode1 Euler solver is used in the Matlab/Simulink with a 10^{-7} s discretization step. The simulation parameters are described in Table 2. LCL parameters are determined in accordance with IEEE 1547 [2] and [15].

Table 2. Simulation parameters.

Parameter	Value	Parameter	Value
V_{dc}	350 V	L_1	10 mH
P	1.1 kW	r_1, r_2	1 Ω , 0.5 Ω
f_g	50 Hz	L_2	1 mH
f_{sw}	10 kHz	C_f	4.5 μF
v_{gj}	68 V	R_d	1 Ω

The simulation results are presented in Fig. 2. Remark that, at 0.1 s a fault is applied by changing the losses values of the low Mosfet of phase a to the following values: $\Delta r_{al} = 5 \Omega$ and $\Delta v_{al} = 4 V$. As it can be seen in Fig. 2 (from 0.1 s to 0.2 s), before applying the flatness based active control, the error $e_j = i_{gj}^* - i_{gj}$, where i_{gj}^* is the grid current reference (with a maximum value of 6 A), indicates that the fault occurs at the phase a . At 0.2 s, where the flatness based active control is applied, the error e_a is reduced, which compensates the influence of the fault.

4 Conclusion and perspectives

The paper proposed a flatness-based approach for the three-phase grid connected inverter for which the faults are modeled as losses.

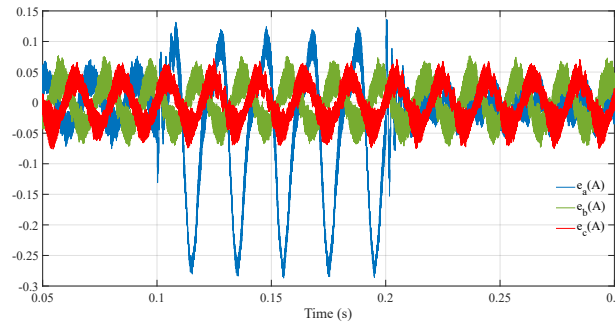


Fig. 2. The grid current errors e_j .

The main contribution is to propose a flat output that is the same for both healthy and faulty models. This result allowed to work with the same active fault control structure at both regimes.

The work perspectives involve coupling the losses and faults estimator with the flatness-based control including the stability analysis and making a comparison with other control methods.

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