Fault-tolerant control for electrical machines and drives based on controllability and observability indexes

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Background, Context

In the context of electrical machine drives (especially synchronous and induction machines), the need of robustness is more and more important in the case of transport, automotive, aerospace, medical robotics and other applications. The faults can appear both on the actuator (machine and its power converter) or in sensors (current, voltage, speed,…). A fault-tolerant control can be used advantageously in that way if the redundancy of the system is sufficient (i.e. the machine can applied a certain torque even if a part of the system is broken).

There are two types of fault-tolerant control: active and passive approaches [Campos 2008] [De Araujo 2014]. This thesis focuses on the active schemes. The goal is to maintain acceptable performance against a set of faults.

In the context of the laboratory AMPERE, predictive control and observability index were already applied respectively to an active front-end rectifier [Martin 2017] and to a sensorless control for an induction machine [Lefebvre 2017]. These competences will be helpful for redundancy analysis and for active fault-tolerant control.

Research subject

The main point to develop in this thesis is the study of a controllability index to quantify the redundancy on the actuators and the definition of an observability index to quantify the redundancy on the sensors.

1) controllability index

The figure 1 shows the idea of the meaning of the controllability index: if it is equal to zero, it is impossible to act on the system and the greater the controllability index, easier the control and redundancy. In non-linear system, this redundancy is clearly dependent on the operating point and on the state of the system. The redundancy can appear at different level : by the use of more than one machine on the same mechanical axis ; into the machine by the choice of current references Id, Iq ; or into the power converter by the choice in the modulation scheme in multi-level or parallel converter.
This new controllability index should be then applied in the following:
- In non-fault mode, a choice has to be made for the references (current references \( I_d \) and \( I_q \), modulation scheme, common mode voltage). The index can be used as part of a trade-off with the efficiency and dynamics performances. As an example, we can include an other term in the cost function of a predictive controller;
- When a fault act on the system, the index can be used to reconfigure the power converter by choosing the new maximum reachable index;
- In fault mode, the controller can automatically change the references/dynamic performance/efficiency to maintain a minimum index value;
- To design a converter, this index can be interesting to choose the best architecture for a particular application.

2) observability index

As underline in background and context, previous works have been carried out at Ampère laboratory about induction machine sensorless control based on the concept of observability index [1]. The main goal of this control is to keep observability index big enough in order to maintain a good speed observation of the machine at low speed by acting on magnetic flux. We propose in this thesis to enhance this concept to the sensor redundancy as we can see on the figure 1. Previous works concern the low level of observability index where the main goal is to avoid the near unobservable areas. In this thesis, we want to extend that to the other limit when the observability index is higher.

This enhanced observability index should be then applied in the following when the fault act on a sensor:
- We can use observer in order to increase the index value;
- In non-fault mode, when a high precision (i.e. a high observability index) is required, a choice has to be made for the references (current references \( I_d \) and \( I_q \), modulation scheme, common mode voltage). The index can be used as part
of a trade-off with the efficiency and dynamics performances. As an example, we can include an other term in the cost function of a predictive controller;
- When a fault act on a sensor, the index can be used to reconfigure the controller by choosing the new maximum reachable index;
- In fault mode, the controller can automatically change the references/dynamic performance/efficiency to maintain a minimum index value;
- To choose a configuration of sensors (for example two high resolution sensors or a high resolution and a low resolution sensors), this index may be interesting to choose the best architecture for a particular application.

**Planned tasks**

- Bibliography about controllability and observability indexes in a general context
- Bibliography about fault-tolerant control for electrical machine drives
- Choice of one or several study cases (type of machine with its associate converter and sensors)
- Definition of one or several controllability and observability indexes and application to the study cases in theory and simulation
- Adaptation of the existing 1.5 kW experiment test-bench to the study cases and tests of the controllability and observability indexes by the way of rapid-prototyping control system using Matlab/Simulink
- Proposition of new control laws based on controllability and/or observability indexes (simulation and experimental tests)

**References**