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Real-time simulation of an electric ship in normal and faulty conditions.

François ROUX · Florian Dupriez-Robin · Guénaël Le Sollicec · François Auger

Abstract Today's requirement for improved electrical systems increase needs for accurate, fast and versatile models. MATLAB™/SIMULINK is a good candidate in terms of average simulation for accuracy, versatility and speed, but for detailed simulation (i.e. designed with the SimScape toolbox) it can be very slow, especially when multiple power converters are simulated. This issue can be solved by real time simulators based on FPGAs like *OP-5607* from *Opal-RT*. With these real-time simulators, complex systems can be simulated with a time step of a few hundreds of nanoseconds. This article presents a new methodology in simulation fields which let researchers to interface fast response power electronics converters and slower physical parts. This new methodology allows designers to evaluate systems at multiple time scales: minutes, seconds and milliseconds. This article emphasizes today's possibilities of simulating a system as complex as the propulsion line of a cruise ship during an entire 30 min trip. Finally, this kind of simulation allows engineers to increase the accuracy of modeling, even to work on realistic faulty conditions.

François ROUX · Florian Dupriez-Robin · Guénaël Le Sollicec
CEA TECH de Nantes, 5 rue de l'halbrane, F-44340 Bouguenais, France, e-mail: francois.roux@cea.fr, florian.dupriez-robin@cea.fr, guenael.lesollicec@cea.fr

François Auger
Nantes Université, Institut de Recherche en Énergie Électrique de Nantes Atlantique (IREENA, UR 4642), CRTT, 37 Bd de l'Université, BP 406, F-44602 Saint-Nazaire cedex, e-mail: francois.auger@univ-nantes.fr

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1 Introduction

Today's concern about environmental issues is pushing public institutions to take action about maritime pollution [1]. Nowadays, many harbors have stringent environmental regulations (i.e. limitation of CO₂ emission, fine particules matters, noise...) [2]. All Electrical Ships (AES) are commonly described as a good way to address these issues. Late trends in ship energy management are about Medium Voltage Direct Current (MVDC) AES [3] because of their high integration possibilities of multiples energy source, capabilities of reconfiguration...

Last decades evolution on power electronics, especially high voltage/current switches (6.5 kV, 1 kA [4]) allows designers to reuse regular/well known medium power topologies in high power converters. This drives the MVDC ship [5], which is the best fit for integration of renewable source/storage energy inherently Direct Current (DC). Finally, new high power Fuel Cells (FC), (e.g. Ballard 200 to 1000 kW marine FC), can be easily integrated as the main power supply for a cruise ship.

The choice of modeling type in power electronics is essential, and is driven by the simulation goals. From our point of view, we have 3 main types of simulations :

- Power simulations showing the power exchanges between all subsystems in a complex system without the complexity of control management. It is useful for testing the global behavior,
- Average simulation is closer to real systems. The linear behavior of converters can be implemented, stability of regulators can be studied [6].
- Detailed simulation is about switches behavior, it is the most accurate way of studying converters and their interactions (high frequency noise, harmonics...) The main issue is computation time: for a dozen of switches in a

simulation, time ratio can reach 1/60 (i.e. for 1 s of simulation, computation time will take 1 min).

The last evolution in field-programmable gate arrays (FPGAs), especially about simulating power electronics [7] on FPGAs, allows researchers to simulate complex systems with a lot of switches in real-time (i.e. unity time ratio) [8]. So, in this article we are going to simulate an AES with MVDC bus supplied by a FC and a battery on FPGAs. The following system is applied to a travel with a fault on DC bus. Simulation on FPGAs allows us to study the faulty period and impacts on the overall system. By means of new FPGAs resolution, this study can be done on multiple times scales: minutes, seconds and milliseconds. The following part of this paper is organized into three sections: section 2 introduces the methodology of this work and how information is exchanged between each part of the system. Section 3 presents used model and interactions between converters and control. Finally, section 4 shows some results of this work.

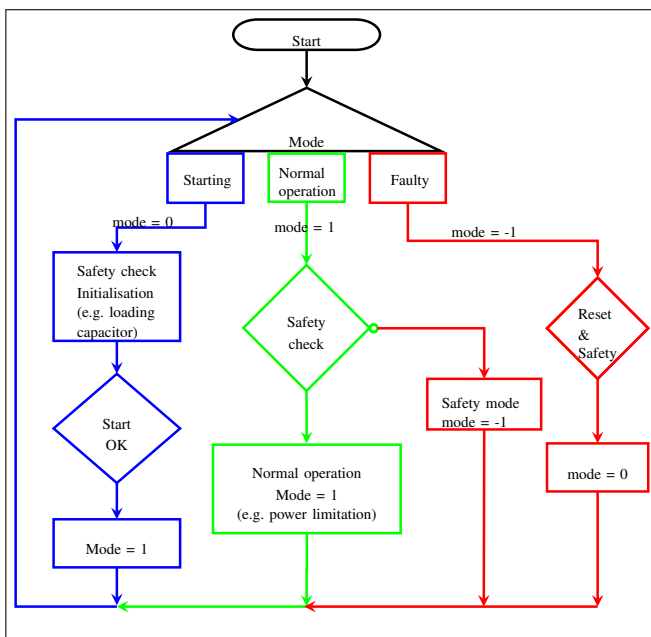


Fig. 1 General view of a supervisor algorithm

2 Design methodology

Models are implemented under MATLABTM SIMULINK environment. The first step is about validation of topologies with the specialized SimScape electronics toolbox, the main objective been simplifying Hardware In the Loop simulation (HILs) and then future Power HILs integration (e.g. decoupling control from physical systems). Once all models are

running together under the SIMULINK environment, electronic part is implemented under OPAL-RT Schematic editor and compiled on FPGAs. Control is intentionally based on very common/well known strategies in order to evaluate the impact of faulty conditions on power electronics without advanced regulation strategies. In order to be closer to the physical behavior, most of the exchanged information between control and physical simulation is done by wired signals. Finally in this paper, we perform a simulation of the propulsion line of an AES, from production to propeller. The overall system was applied to a cruise ship 30 min long travel (from Fromentine to île d'Yeu. e.i. from a continental french harbor to a near french island). Eventually FPGAs programming allows us to explore faulty configurations like creating short circuits on the DC bus.

3 Model and parameters

In this section, we will present as exhaustively as possible the model and the parameters of this work. We will start by the Power Management System (PMS), which manages elements in this simulation, then the electrical model of power converters and their close control. Finally, we will show how the mechanical response of a ship impacts the electrical part.

Models and control are always managed by a close safety supervisor. Its first purpose is to manage starting/faulty conditions, high level implementation is presented in Fig. 1. It is in these close supervisors that safety and respect of standards are managed. The main practice that we are following is *IEEE Std 1709TM2010* about faulty tolerance in MVDC, which mainly consists of 10% tolerance on DC bus and 10 ms to clear faulty condition [5]. The second purpose is the application at converters level of PMS control signals and limitations.

3.1 General view of the case study

In ship, symmetry/redundancy is a key for safety, in case of failure of a part of propulsion line the ship can return to the nearest harbor with the remaining power. Because of that, we are only studying a half ship, the global architecture is presented in Fig.2.

3.2 PMS

The PMS is the supervisor of the entire ship. Its goal is to give orders to every converters supervisors :

- start and stop,
- power limitation,
- high level control (i.g. DC bus level, battery charge, etc),
- dispatching between power sources etc.

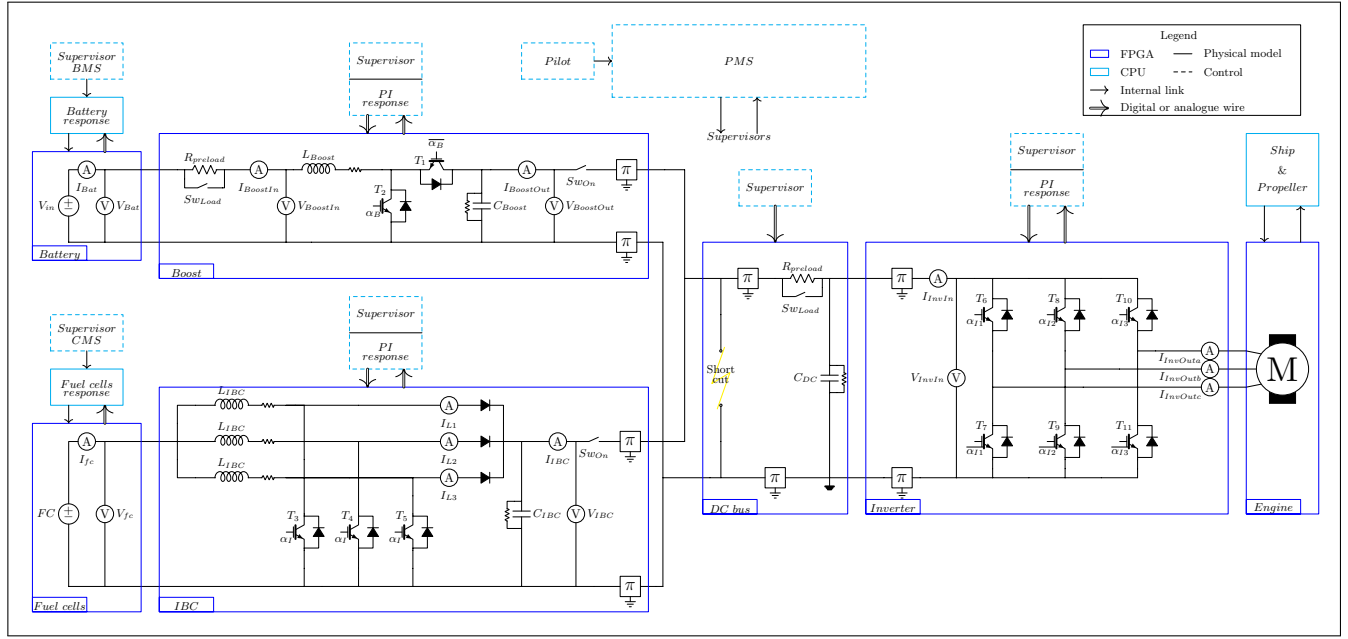


Fig. 2 General view of the studied electrical architecture

The PMS is based on information provided by converter supervisors, state (starting, steady and fault) and few other information (power, Stat Of Charge (SOC)...). The PMS algorithm is based on the algorithm of supervisors.

3.3 FC and DCDC converter

The FC used in this work is based on [9] (MATLABTM SimScape Model). The associated converter is an Interleaved Boost Converter (IBC) (Fig. 2), because of inherent operation of FC, this converter is not reversible. This converter is current controlled by a single Proportional Integral (PI) controller. Design of IBC is based on boost equations [10]. Because of the unavailability of data sheet of 800 kW FC we use data sheet of a 50 kW FC. In this purpose, in order to preserve dynamics and behavior, current provided to the FC model is divided by 16.

$$D = 1 - \frac{V_{in_{min}}}{V_{out_{max}}} \quad (1)$$

$$L_{Boost} \geq R_{ch} * \frac{D * (1 - D)^2}{2 * F_{Scw}} \quad (2)$$

$$C_{Boost} \geq V_{DC} * \frac{V_{out} * D}{F_{Sw} * \Delta V_{out} * R_{ch}} \quad (3)$$

3.4 Battery and DCDC reversible converter

The battery used in this work is based on [11] (MATLABTM SimScape Model). In this topology, the only converter which can act as an Active Front End (AFE) is the battery DCDC

converter. Its main goal is to control the bus voltage. As an AFE, it must be reversible in order exchange energy with the bus. We choose a well known boost medium power topology presented in Fig 2. This boost is controlled by two cascaded PI controllers, the outer loop controls bus voltage and inner loop controls current [6]. The design of the boost converter is based on Eqs. 1 to 3.

Table 1 Simulation parameters

| Fuel cell (SimScape) | IBC | Controller |
|--------------------------|---------------------------|--|
| Type : PEMFC | Frequency : 20kHz | Current regulator |
| Power : 50 kW | Number of legs : 3 | $K_i : 2.64 \cdot 10^{-4} s^{-1} \cdot A^{-1}$ |
| Voltage : 625 Vdc | $L = 0.115 H$ | $K_p : 3.70 \cdot 10^{-5} A^{-1}$ |
| | $R_L : 50 \mu\Omega$ | Saturation : [0 0.95] |
| | $C : 0.1 mF$ | |
| | $R_C : 50 k\Omega$ | |
| Battery (SimScape) | Boost | Controller |
| Type : Lithium-ion | Frequency : 20kHz | Voltage regulator |
| Rated Capacity : 1000 Ah | $R_{on} : 0.1 m\Omega$ | $K_i : 1158 A/(V \cdot s)$ |
| Voltage : 800 Vdc | $C : 3.11 mF$ | $K_p : 3.62 A/V$ |
| | $R_C : 50 k\Omega$ | Current regulator |
| | $L : 50 \mu H$ | $K_i : 0.018825 s^{-1} \cdot A^{-1}$ |
| | $R_L : 50 \mu\Omega$ | $K_p : 0 A^{-1}$ |
| | $R_{Preload} : 10 \Omega$ | |
| Engine (PMSM)[12] | Inverter | Controller |
| $L_d = L_q : 0.476 mH$ | Frequency : 20 kHz | Regulator |
| $R_s : 1.502 m\Omega$ | $R_{on} : 0.1 m\Omega$ | $K_i : 200 V/(A \cdot s)$ |
| $p : 8$ | $C : 3.11 mF$ | $K_p : 0.1 V/A$ |
| Flux linkage : 3.55 | | Saturation : $\pm Vdc$ |
| Rated speed : 200 rpm | | |

3.5 DC bus

A capacitor has been introduced between DCDC converters and the DCAC converter, to ensure a better stability, for starting stage a preload resistor and its switch were added (Fig. 2).

3.6 DCAC converter and motor

Finally, a two level DCAC converter (Fig. 2) converts from DC bus to the Alternative Current (AC) Permanent-Magnets Synchronous Motor (PMSM). The control is based on Direct Torque Control (DTC) [13]. Pulse Width Modulation (PWM) generation is managed by specialized OPAL-RT digital outputs.

3.7 Ship and propeller

The ship model is based on [12] and experimental data. Table 2 shows power over velocity of the studied ship, total resistance to ship advance is computed by $R_{ship[N]} = P_{[W]}/v_{[m/s]}$. Eq. 4 shows the result of a second order linear regression between resistance and velocity, which is used as model for the ship resistance.

$$R_{ship} = 371 V_a^2 + 24 V_a \quad (4)$$

The estimation of external characteristics of the propeller is based on *OpenProp* [14]. Multiple analysis were performed in order to meet ship linear velocity, required thrust and rotational motor speed. Propeller characteristics are presented in Table 3. Torque and thrust of propellers are usually computed from an adimensional advance (5), thrust (6) and torque (7) coefficients [15].

$$J_s = \frac{V_a}{\omega D} \quad (5)$$

$$T_{Prop} = K_T(J_s) \cdot \rho \omega^2 D^4 \quad (6)$$

$$Q_{Prop} = K_Q(J_s) \cdot \rho \omega^2 D^5 \quad (7)$$

| | | | |
|----------|------------------------------------|--------------|---------------------|
| J_s : | advance coefficient | Q_{Prop} : | torque [Nm] |
| K_Q : | torque coefficient | T_{Prop} : | thrust [N] |
| K_T : | thrust coefficient | V_a : | ship speed [m/s] |
| ρ : | water density [kg/m ³] | ω : | rotor speed [rad/s] |
| D : | propeller diameter [m] | | |

OpenProp computes thrust and torque coefficients from external characteristic propeller. Table 3 summarizes parameters which feed *OpenProp*. These K_T , K_Q versus J_s coefficient are feeding the propeller model ((5) to (7)). At last, because of the unsymmetrical behavior of propeller for positive and negative advance coefficients, negative thrust is decreased by 50%. Finally fundamental dynamics relations are

applied to compute the ship and rotor speed (8) to (9).

$$m\dot{V}_a = \sum force = T_{Prop} - R_{Ship} \quad (8)$$

$$J\dot{\omega}_{rotor} = \sum torque = \Gamma_{rotor} - Q_{Prop} \quad (9)$$

m : ship mass [kg]

Γ_{rotor} : rotor torque [Nm]

J : inertia (rotor + Propeller) [kg.m²]

Table 2 (half) ship power and velocity

| Engine power [kW] | Ship velocity [kn] | Resistance [kN] |
|-------------------|--------------------|-----------------|
| 485 | 21.2 | 44 |
| 340.5 | 18.8 | 35 |
| 280.5 | 17.6 | 31 |
| 243.5 | 14.1 | 20 |
| 83 | 11.8 | 13 |
| 26.5 | 8.2 | 8 |
| 0 | 0 | 0 |

Table 3 ship power (half ship) and velocity

| Ship | Propeller |
|---------------------------------|------------------------------|
| Maximum thrust : 44 kN | Diameter : 2.3 m |
| Speed : 20 kn | Number of blades : 3 |
| Ship mass : 107 t | Hub diameter : 0.23 m |
| Inertia : 1440 kgm ² | Rotor speed : 200 rpm |
| | Propeller type : NACA 65A010 |

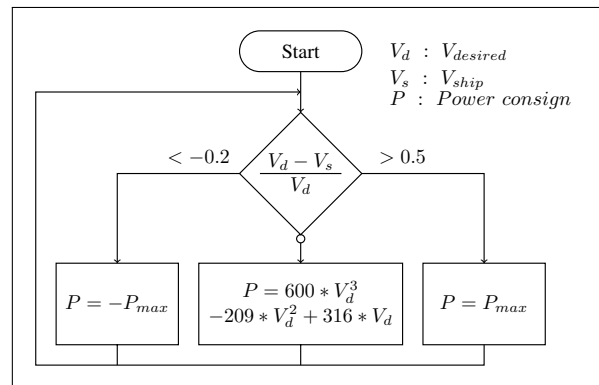


Fig. 3 Pilot logigram

3.8 Pilot

Pilot determines the level of power applied to the propulsion engine. Basic rules are presented in Fig. 3, in order to achieve the ship travel (speed over time) defined in Fig. 4 (Speed envelope) 5 kn into harbor and channel, 20 kn at sea.

3.9 Short circuit

As an illustration of advanced simulation possibilities on FPGAs, we implement a short circuit between DC bus and DCAC converter. To this aim, line impedance has been added at relevant locations (see Fig. 2). To ensure compliance with *IEEE* standard, a short circuit of a duration $< 0.01s$ was performed. In these conditions, the system should stay in steady state.

4 Results

4.1 Evaluation of the model on 30 min travel

Fig. 4 shows the modeled speed of the ship during the 30 min case study. On this figure, we can see the evolution of speed (rotor and linear) over speed shape. The simulated ship is within specifications. The third part emphasizes implemented pilot commands (Fig.3).

Fig. 5 shows power exchange between source (FC), storage (Battery) and engine. We can see that the battery is charging for the first 20 minutes until it reaches 80% of SOC (limit which has been chosen in the PMS as the end of the force battery recharge). So on FC curve a drop occurs when battery is fully charged. As expected, we can see that the FC supplies an average power to the system (engine power and charging the battery), battery is continuously working as an AFE (i.e. keeps DC voltage bus constant) whether its charging or discharging. On the engine section Fig.5, the pilot commands are displayed.

4.2 Faulty study

Fig. 6 shows the impact of the short circuit on the DC bus. As we can see, the time counter of the boost (used as a watchdog) is counting until its end. If it reaches 10 ms the system switches in safety mode (all switches are forced open) and is waiting for a reset. But in this case, we want to cause a fault that does not prevent the system from continuing to work. On the engine session we can see the reaction of the engine : on magnified views, the engine speed decreases during short circuit, as expected, then the speed increases because of the PI controller response during fault, but everything is back to normal within a second. At time $t = 0.2 s$, a second fault occurs, because the motor restarts, and thus starts to draw energy from the DC bus again, whereas during the first fault it was supplying energy. This phenomenon is amplified by the saturation state of the controller. Finally we can see one limitation of this set up, engine currents are limited at 1600 A because of acquisition line saturation.

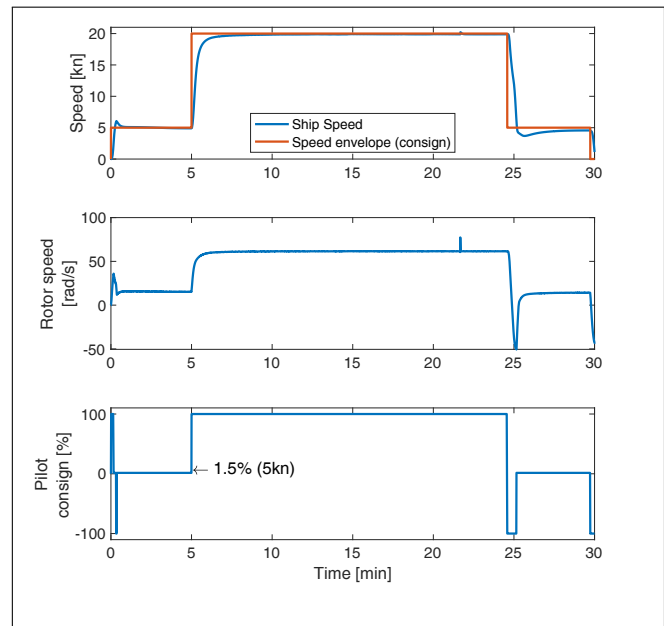


Fig. 4 full travel

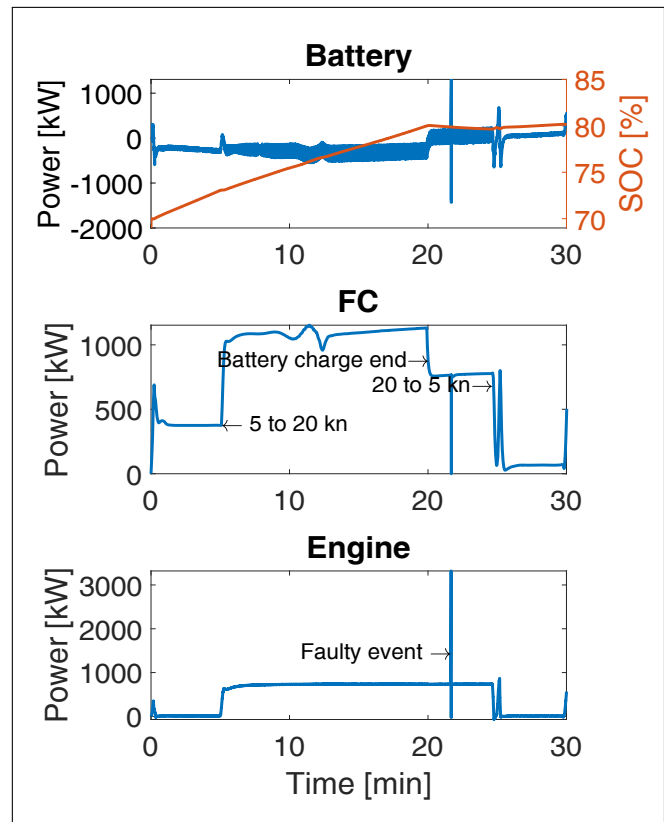


Fig. 5 Power through converters

5 Conclusion

As described in this paper, a new bit-stream approach dedicated to power electronics in FPGAs brings electronics simulation to the next level in terms of accuracy, simulation time

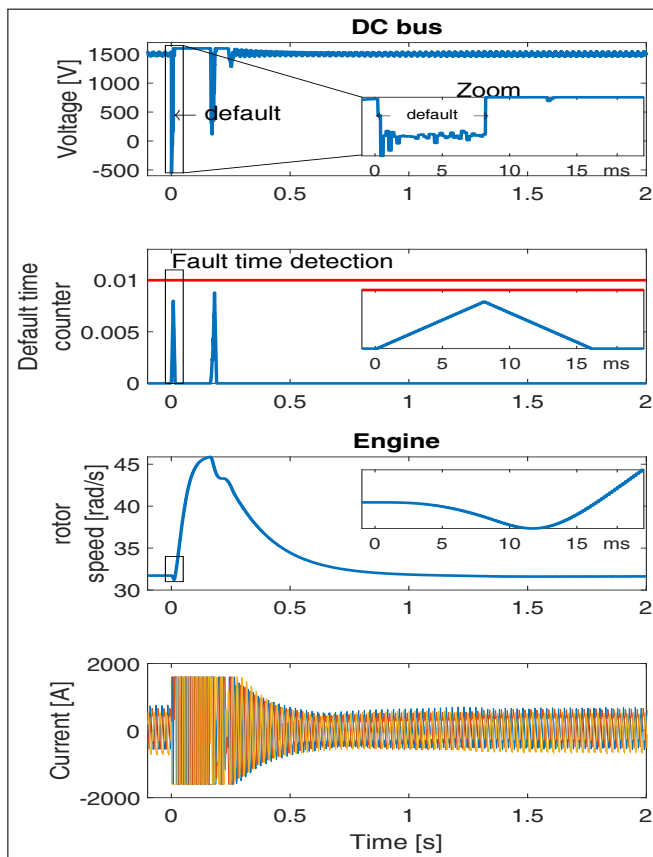


Fig. 6 Faulty and recovery

and versatility. Engineers with the same model can explore multiple aspects of a system with a high level of fidelity with an improved in simulation time. This article reveals a lack about control strategy : PI control is enough for quasi steady state but not relevant when faulty conditions occur, but it was not the objective. From our point of view, this article is a good baseline, future development could explore different control strategies. The objective was to develop a method which allows engineers to simulate a system with different dynamics (power electronics [μ s], engine [ms], hydrodynamic and inertia [s]) with high accuracy and long term impacts assessment. Moreover, with this kind of simulation, research on power, even energy management system can be pursued with detailed model rather than less accurate average models. These kind of results can only be obtained using FPGAs, CPU simulation would be very time consuming. Finally, this method is a step forward of HIL toward Power HIL and rapid control prototyping.

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