Paper presented at the 13th European Conference on Power Electronics and Applications
(EPE-2009), September 8-10 2009, Barcelona, Spain

Real-Time Simulation of a PMSM Drive in Faulty Modes with Validation Against an Actual Drive System

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Keywords

Real time Simulation, Permanent magnet motor, Test bench, Adjustable speed drive, Fault recovery strategy.

Abstract

This paper presents real-time simulation results of a Permanent Magnet Synchronous Machine (PMSM) Drive in faulty and non-standard modes and validates these against an actual industrial PMSM drive system. The paper will put emphasis on the test of special and faulty modes in PMSM drives. Results of real-time simulation of a PMSM drive with an open phase and in passive mode (with all IGBTs switched off) will be presented. These working modes are usually difficult to simulate in real-time because of the fixed-causality models used in the real-time simulator.

Introduction

Today, before using a motor controller with a real motor drive, it is a common industrial engineering practice to test a controller against a motor model simulated in real-time. This has several advantages. For example, the simulated motor drive can be tested with borderline conditions that would damage a real motor, often a costly prototype. The motor itself may be under development in parallel to the controller and may therefore not be available. While testing, a controller is interfaced with the real-time simulated motor drive through a set of proper I/Os: this is called hardware-in-the-loop (HIL) simulation. Such motor drive simulation is required by motor drive manufacturers to speed up development and testing time by using real-time simulation before making tests on physical prototypes.

Modern, fast digital motor drive controllers can have a very small sampling time below 10 microseconds and therefore require that its real-time, simulated motor have a computational time much lower than this value. This requirement exists because the computational time for the model (including the I/O access times) adds a delay in the loop of the final closed-loop response of the controlled motor. If this added delay is too large (a real motor has no such latency), the HIL simulation may diverge from the response of the controller with a real motor.

Such ultra-fast real-time simulators have been demonstrated in the past [1]. These simulators require the use of interpolating methods to cope with multi-kHz inverter and fixed-causality models to reach this performance. The use of fixed-causality method then requires additional coding for all non-standard modes. For example, in freewheeling regenerative mode (all IGBT gates turned-off with Back-EMF voltage greater than DC-link voltage), there is an apparent causality reversal in the model and special code must be added to conduct the simulation.

This paper will present real-time simulation results of a PMSM drive in faulty and free-running mode and compare the results with an actual system. The work is an extension of the work described in [1] to include the tests of these non-standard modes. The paper will compare the results of the real-time models with actual results from a real Internal Permanent Magnet (IPM) motor drive used at Mitsubishi Electric Corp.

Current models for the real-time simulation of PMSM drive.

In [1], a complete validation of a PMSM drive against an actual system was described. The validation was made by comparing the response of an actual 7.5kW IPM drive against one simulated on the RT-LAB platform with an HIL-connected controller. In both cases, the IPM drive was controlled by a dSpace Rapid Control Prototyping system.

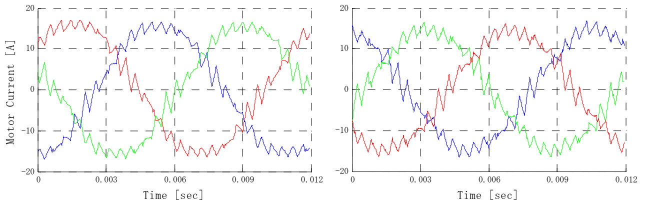
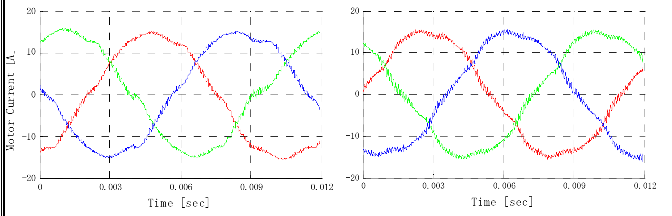
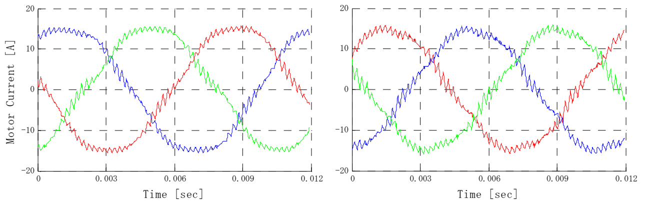
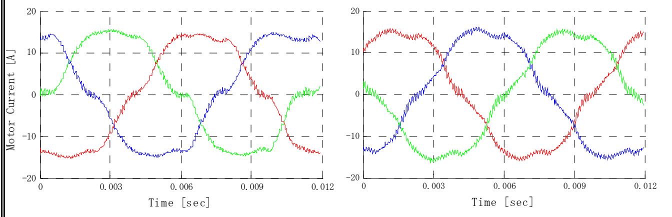
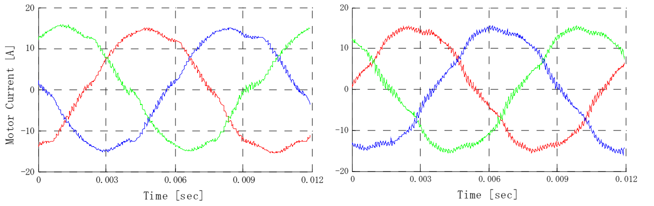
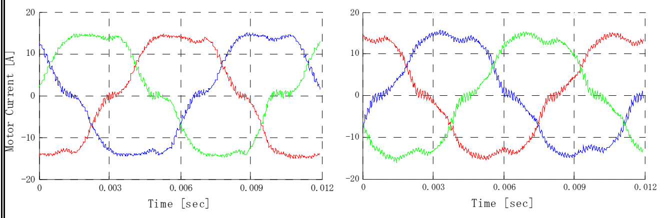
Effect of PWM frequency (fixed dead time: 4.2μs)		Effect of dead time (fixed 9 kHz carrier)	
HIL simulation	Actual System	HIL simulation	Actual System
 PWM frequency: 2.25 kHz		 Dead time: 4.2 μs	
 PWM frequency: 4.5 kHz		 Dead time: 8.4 μs	
 PWM frequency: 9 kHz		 Dead time: 12.6 μs	

Fig.1. Summary of validation results of an HIL-simulated IPM against an actual IPM drive.

The RPC controller had a sampling time of 55 µs and the RT-LAB simulator ran at a sample rate of 10µs. As can be seen in Fig.1, the HIL simulation closely matches the actual plant results even in such details as dead time effects. To achieve this accuracy, the inverter and machine were modeled using fixed causality modeling and with an interpolated inverter model. More detailed results can be found in the reference mentioned.

Nevertheless, this HIL simulator had the major drawback that it could not run special or faulty modes, such as when one motor phase is opened or when the controller stops sending pulses to the inverter. The main objective of this paper is to propose such a PMSM drive (IPM is equivalent to PMSM in terms of model) model with extensive fault capability.

Proposed fault-capable inverter model compatible with real-time simulation

In this paper, we validate the use of a novel type of inverter model that will support fault simulation. The model is hybrid: the PWM voltage interpolation is still made with controlled voltage sources while high impedance effects are modeled with switches that are part of a global solver, such as the SimPowerSystems (SPS) blockset. The switches (SPS ideal switches) are connected in series with the controlled voltage sources in this model. A complex logic controls the state of the switch according to the gate status (pulsing or non-pulsing) and the voltage across the switch to simulate rectification effects. The switches can also be forced OFF to simulate open-phase conditions. Finally, the use of a global solver ahead of the switching-function eases the connection of other devices to the drive, such as dynamic braking resistors.

The PMSM model used in the real-time model tests is a standard dq-type model that assumes sinusoidal back-EMF and constant Ld and Lq values. All RT-LAB simulation tests are conducted using a numerical model of the controller simulated on the simulator itself. Comparisons in HIL mode with the actual controller will be presented in a future work.

Table II: MELCO IPM7.5kW Parameters

nominal output	7,500	[W]	 7.5 kW IPM
number of pole	3	[nb of pole]	
Inertia	144.6	[1e-4*kg*m^2]	
nominal rated current	26.0	[A(rms)]	
max current	39.0	[A(rms)]	
resistance(phase)	0.1200	[ohm at20degree]	
d-axis inductance(phase)	2.984	[mH]	
q-axis inductance(phase)	4.576	[mH]	
d,q-axis induced voltage constant	1.0432	[Vrms/(rad/s)]	
rated rotation speed	1,800	[r/min]	
max rotation speed	2,700	[r/min]	
rated torque	40	[Nm]	
max torque	60	[Nm]	
PWM frequency	2250	[Hz]	

Validation of a real-time model against an actual Interior Permanent Magnet (IPM) motor drive

The actual drive parameters are listed in Table II. The proposed inverter model is compared to actual measurements on this drive for the following cases:

- free-running mode (i.e. no pulse sent to the IGBTs)
- free-running with active breaking (2-phase and 3-phase)
- active control with one opened phase

From a model point of view, IPM is just a special case of PMSM that is modeled with the same well-known dq-type model equations found in the literature (see [9] for example). The model is linear type and does not include any saturation effects.

Real-time simulation of a PMSM drive in free-running mode.

The first important non-standard working mode tested in this paper is the so-called ‘free-running’ mode. This mode occurs when all IGBT gates are put LOW state, leaving the inverter in high-impedance state (as seen from the motor). In this mode, the anti-parallel diodes do not turn ON because the motor speed results in back-EMF amplitude lower than the DC-link voltage.

Normal free-running mode

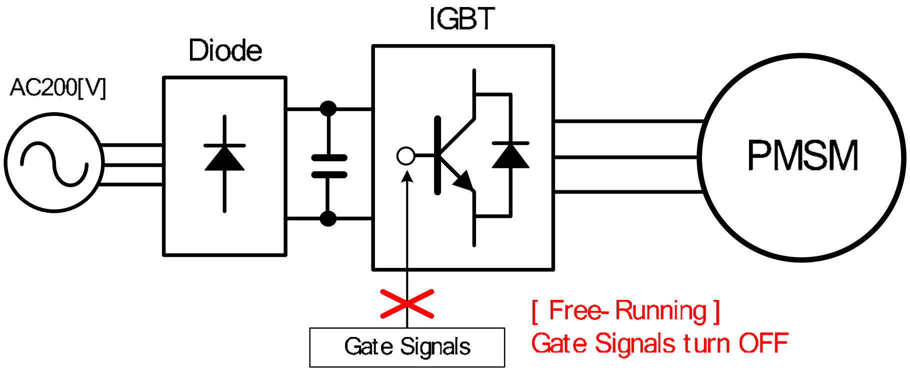


Fig.2. PMSM Drive in free-running mode

Fig.2 effectively summarizes this test in which the IGBT gate signals are turned OFF. In this test, the PMSM drive speed is driven to 1000 RPM and the IGBT gate signals are suddenly shut off between 0.2 and 0.25 sec. An excellent agreement is found between the actual drive results of Fig.3 and the real-time simulation results at 10 µs of Fig.4. In particular, the back-EMF voltage is visible during the shut-off time period. In this figure, and others to follow, the upper trace shows the motor speed, the second trace shows the motor terminal voltage, the third trace is the motor currents and the last trace is the commanded Iq value, usually proportional to the electric torque produced by the machine.

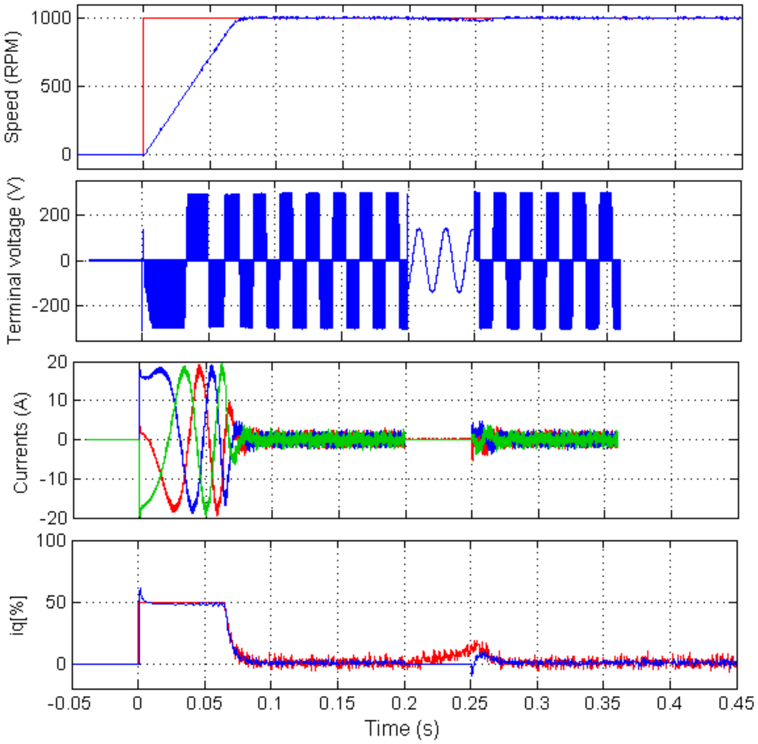


Fig.3. Free-running mode test: Actual drive

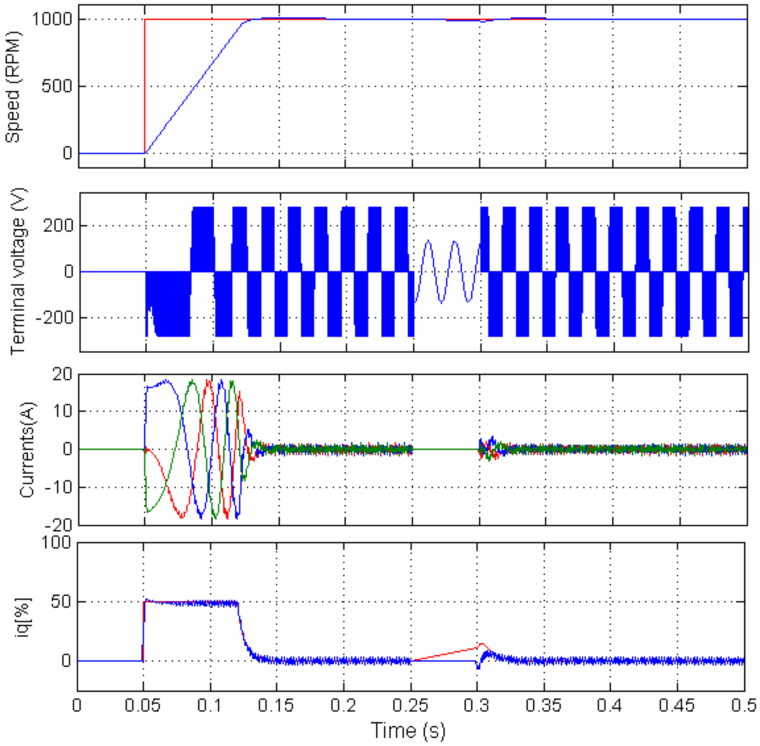


Fig.4. Free-running mode: Real-time simulation @ 10 µs

Free-running mode with dynamic braking

The free-running mode can be accompanied by a dynamic braking mechanism in which a resistance bank short-circuits the machine terminals and thereby dissipates the motor electro-mechanical energy until its rotation ends. This dynamic braking approach is depicted in Fig.5. The real-time simulation results are shown in Fig.6 for two- and three-resistor dynamic breaking. The simulation results agree completely with measurement on the actual drive (not shown).

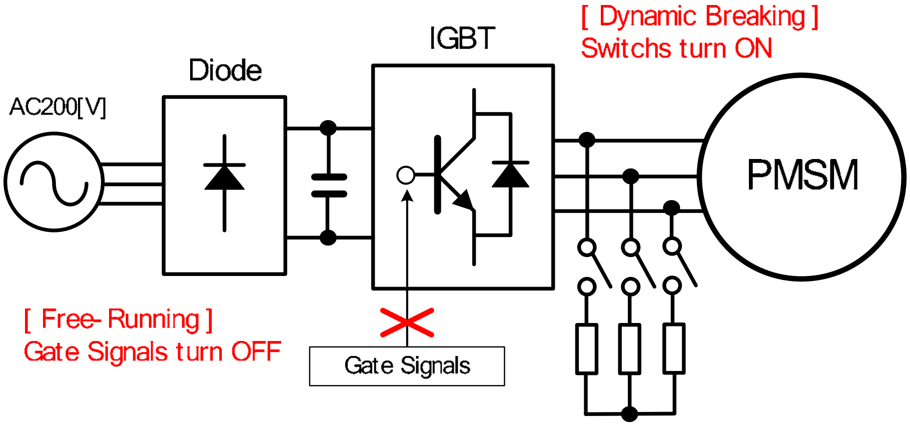


Fig.5. Free running mode with dynamic braking

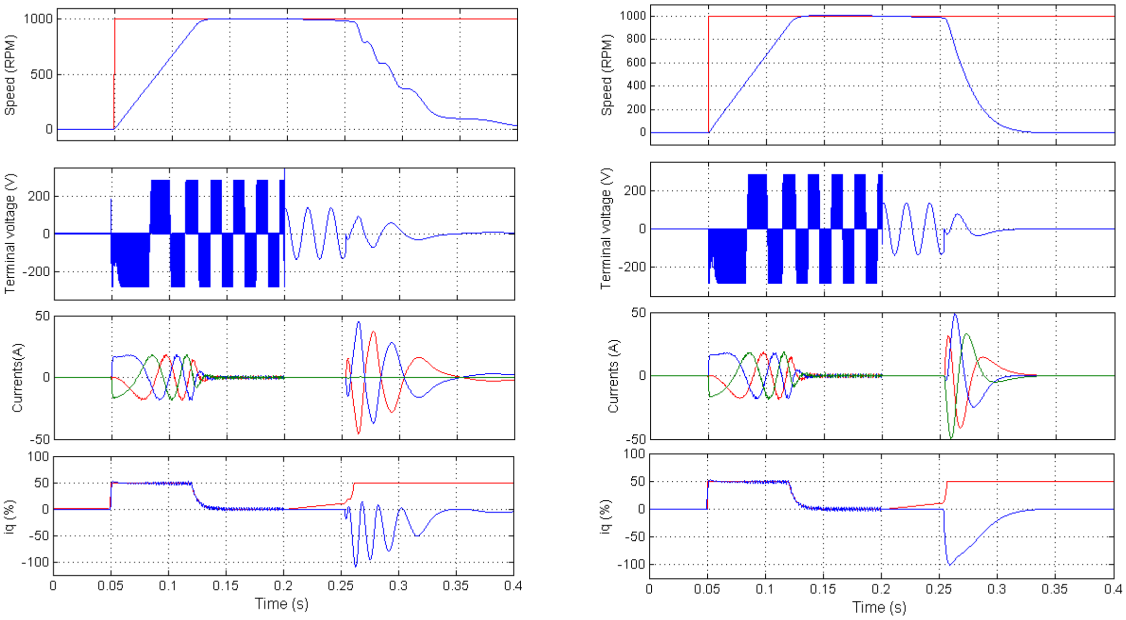


Fig.6. Free-running mode with two-phase (left) and 3-phase (right) dynamic braking : Real-time simulation @ 10 µs

Real-time simulation of a PMSM drive with an open-phase fault

Another important non-standard working mode is when one phase opens between the inverter and the motor. In the proposed model, this open-phase fault is part of the solver part of the model (SPS ideal switch) and is not difficult to model. However, to obtain a clean terminal voltage and limit numerical instabilities, the open-phase resistance must be limited to a certain value.

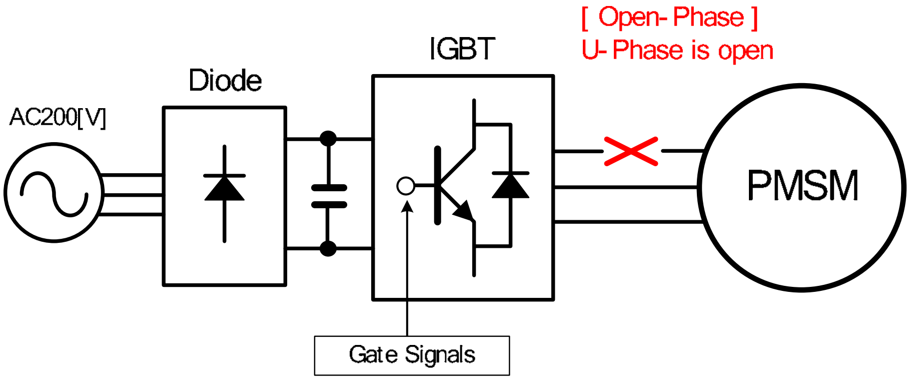


Fig.7. PMSM Drive with an open-phase

The test result shown in this abstract compares an actual drive response in faulty open phase configuration with the result of a real-time simulation. The real-time simulation result was made with a sample time of 10 µs and the open-phase resistance (*Ropen*) was limited to 200 Ω in this case. This is clearly visible on the third plot of Fig.9 (red trace near the zero axis), where the open-phase current cannot be forced fully to zero when PWM action is taking place.

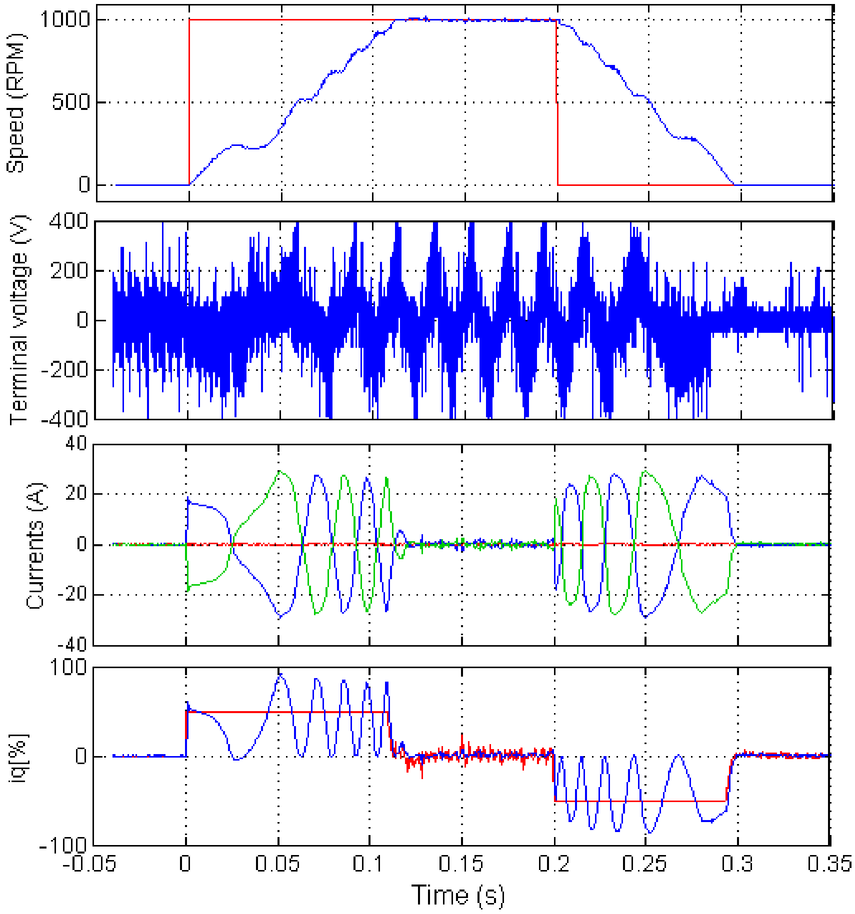


Fig.8. Open-phase fault results (Actual drive)

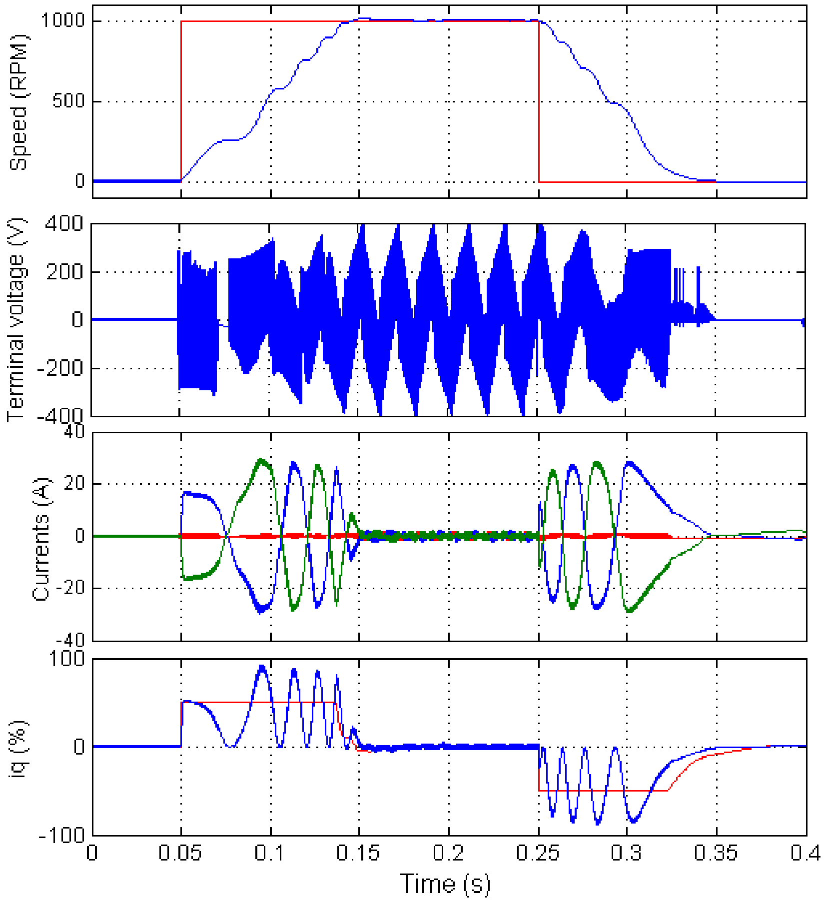


Fig.9. Open-phase fault results (RT-LAB simulation @ 10µs)

Although the actual and simulated drives qualitatively have very similar responses, these is a difference in the acceleration of the machine. The actual machine accelerates more slowly. Tests made with SimPowerSystems only at 1µs (because it has a non-interpolated solver) produce the same acceleration as the proposed real-time model. This difference in results may be caused by the use of a linear PMSM model without saturation. Indeed, one can notice that the current levels in open-phase mode are higher than regular mode. In a real machine, saturation effect may lead to a decrease in torque production with regards to the ideal case. The effective Ld and Lq values of a real machine varies with saturation and its back-EMF is not purely sinusoidal, two conditions that are not considered in the standard dq-type PMSM model.

The same inverter model could be used with a Finite-Element based motor model that would include saturation effects. Such a model, like the one described in [7], would probably lead to a better match between simulated and actual results.

Conclusion

An improved 2-level inverter model with advanced fault capability has been proposed in this paper. The model is based on an interpolated switching-function approach coupled with the SimPowerSystems solver to mimic the series high-impedance effects that occur in special and faulty working modes of this type of drive.

This paper made a validation of the model against an actual drive in free-running, dynamic braking and open-phase modes. Comparison of the results shows a very good match between the simulation and the actual device. In open-phase mode, a slight difference in acceleration is present, however this may be caused by the use of a linear d-q PMSM model.

One drawback of this model is that the open-phase impedance (open-phase or free-running mode) cannot be set arbitrarily high because of numerical stability concerns. The main reason for that is the presence of a coupling delay between the fixed-causality part (interpolating inverter) and the solver part (modeled in SimPowerSystems).

Future work on this subject includes the validation of this model in HIL mode with an actual Power Electronic Controller (PEC). This work will be presented in a future paper.

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