Project title	Models of electrical drives for wind turbines
Project number	TG1-2
Organisation	Chalmers University of Technology, Electric Power Engineering
Project leader	Ola Carlson
Other participants	Joachim Härsjö (PhD student)
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Participating companies	Göteborg Energi

Project description

The goal of the project was to further develop the models of the generator during internal turn-to-turn short-circuit in order to attain knowledge which can be used in the development of fault detection methods. The generator type investigated in this project is the permanent magnet synchronous machine (PMSM), which is used in the Big Glenn wind turbine in Gothenburg. According to the performed literature study, the turn-to-turn fault is the most common electrical fault for electrical machines but any effective fault detection method for this type of fault does not exist. Hence, the modelling of PMSMS with turn-to-turn fault with the aim using the developed models for generation knowledge that could be used for fault detection was selected as the topic for this project. The generator was modelled both analytically and using finite element software, where the finite element model was used for both the verification of the analytical model, and to evaluate the faults impact on the electromagnetic forces of the generator.

The project description is specified in the following subtask:

1. Further improve the models derived in stage 1 in order to increase model accuracy and investigate additional aspects of the model which were not considered in the first part, such as magnetic saturation. In addition, the models should expand the model so that it is able to model machines with parallel winding, which is common for larger machines such as the ones used in wind turbines.

2. Investigate the machine controller reaction to operating a faulted machine. The introduction of a controller can introduce new, more effective quantities to monitor for fault detection other than the machine current as presented in stage 1.

3. Use the FEM models to investigate the faults impact on the electromagnetic forces of the machine.

4. Verify the simulation results in an experimental setup consisting of a purposely rewound machine, where the rewinding allows the possibility to short-circuit some of the machine turns in a controlled manner. The experimental testing includes both the fault impact on the machine currents and the faults impact on the electromagnetic forces of the machine.

Results

The derived analytical model presented comparable simulation results as the FEM models, where the benefit of the analytical model is that it can be simulated in the range of seconds to minutes where an equivalent simulation of the FEM models would take hours or days. The analytical model has been verified for various operational conditions; generator operation with a pure resistive load for various loads and speeds and during ideal converter operation. Figure 1 presents the simulation results where the faulted FEM and analytical model are compared during dynamic simulation where a machine current controller is used to achieve the desired machine torque.

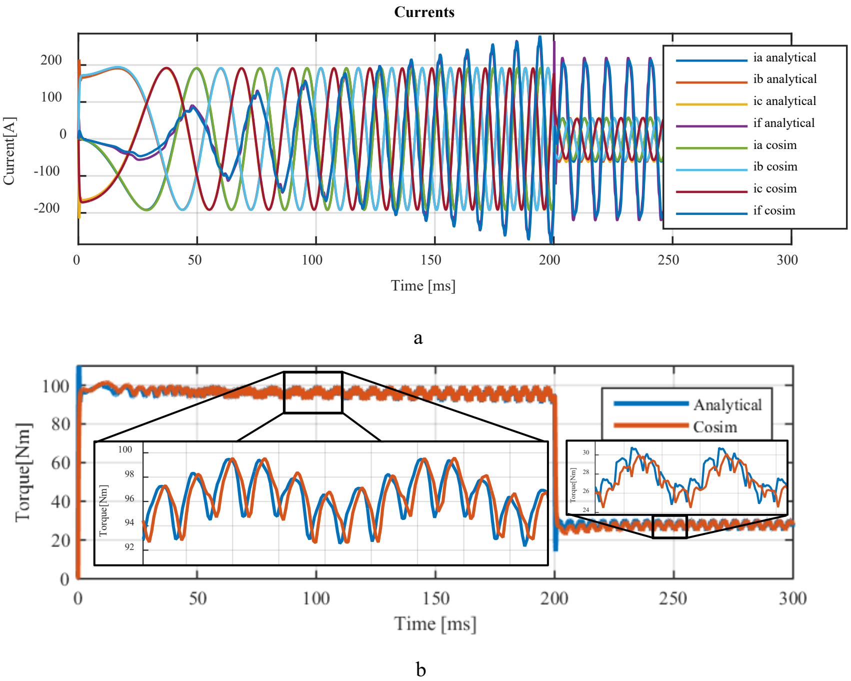

Figure 1 Currents and torque from analytical model and the co-simulation which includes the FEM model during ideal converter operation. The torque reference is stepwise reduced from 100 Nm to 30 at 200 ms.

The analytical model was extended so that it is able to model machines with parallel windings, where it was generically extended so that any number of parallel windings can be included in the model. The circulating currents which occurs due to the turn-to-turn fault (because of the reduced induced voltage in that branch compared to the non-faulted branches) for machine was investigated and it was concluded that for less sever faults the circulating current is less than rated current and should therefore not pose any major issues for the machine. However, even though the amplitude of the circulating current may be very large, the fault current in the short-circuited loop typically is several times greater than the rated current the machine should therefore be stopped in order to limit the damage.

A turn-to-turn fault will (because of its inherent nature of the fault current to oppose any change in flux) not introduce any additional saturation in the machine, if anything it will reduce the saturation level. As a result, if a linear model of a non-faulted machine presents acceptable results with the modelled machine during normal operation, then a linear model of the faulted machine will present similar agreement.

With the implemented control structure, it was proven to be more effective to monitor the machine power rather than the machine currents (as suggested in the first part), as the fault consumes some power the controller compensates which results in less power than what to be expected during generator mode. The fault introduces torque oscillations, which results in power oscillations since the controller tries to keep the speed of machine constant. Figure 2 presents the machine torque for various degrees of short-circuited faults. The machine model used in this simulation consists of 20 turns in one phase, i.e. one turns fault equals 5% of the phase being short-circuited. There are other electrical quantities that can be used such as the amplitude of the current harmonics or the phase angle of the current, but these quantities are not very effective to use as early detection when only a single or very few turns are short-circuited.

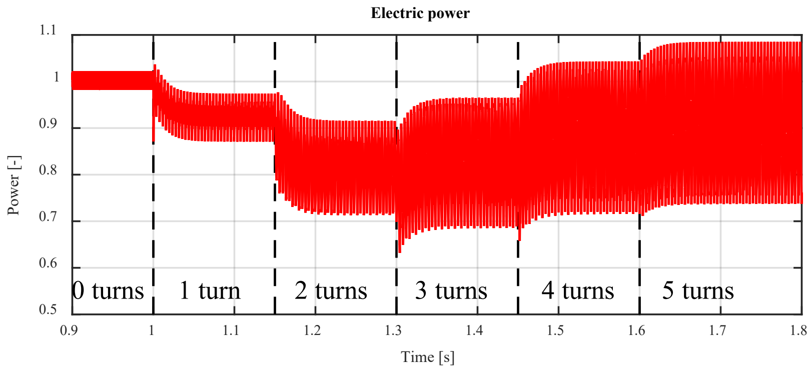

Figure 2 The output power of the converter driven model during generator mode.

The faults impact on the electromagnetic forces was investigated to see if the fault can more effectively be detected using the mechanical vibrations of the machine frame instead of any of the electrical quantities. Because the fault opposes the change the airgap flux, the symmetry of the airgap flux is lost resulting in an unbalances attraction force between the rotor and the stator. Figure 3 presents the radial normal force in the airgap (attraction force between rotor and stator) at a single time instant, and as can be seen the normal force for the non-faulted machine presents similar values at 10° and 190° (mechanical). As these forces are 180° separated they are in opposing directions which result force close to zero. In the case of the faulted machine the normal force is reduced at 10°, hence the resulting force for the faulted machine is no longer zero. This difference results in increased vibrations with a frequency at two times the fundamental frequency; it is two times frequency as the orientation of the magnets does not matter as the fault opposes changes in flux regardless.

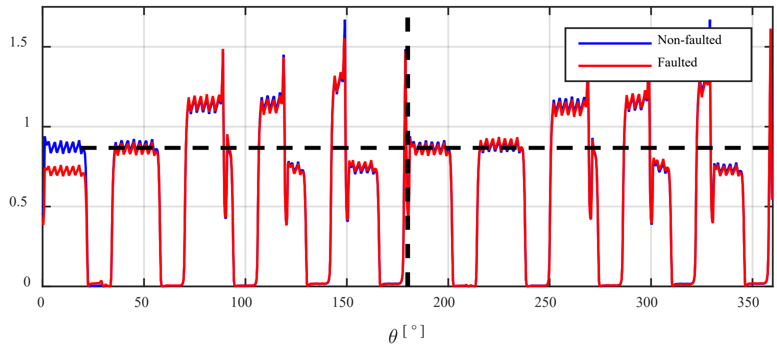

Figure 3 Normalized normal component of the air-gap flux density for one time instance during generator operation for faulted and non-faulted machine model

Using a test setup in the lab, the simulation results was verified. The setup used a rewound machine which had access to inner parts of the winding so that up to 4 turns (about 0.5% of the total phase winding) could be short-circuited. As was done for some simulations, the test setup was operating as a generator with a resistive load. Because of the relatively small portion of the machine being short-circuited, the impact on the machine current was not measurable, showing that monitoring the current harmonics is not the most effective detection method for small fault. However, the fault caused a measurable difference in the machine vibrations, as the amplitude of vibration at two times the fundamental (electrical) frequency increased, see figure 4. The non-integer are caused by the slightly oval shape of the machine used in the lab setup.

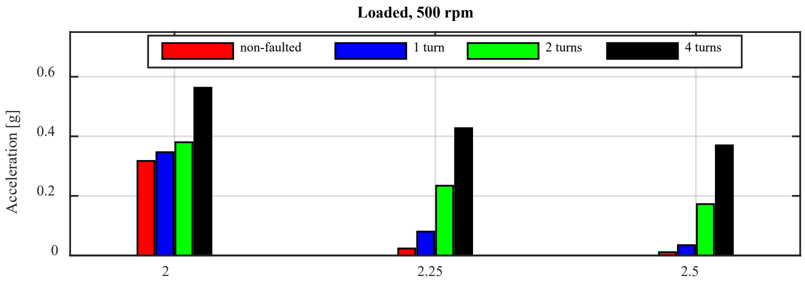

Figure 4 Fourier analysis of the measured stator vibrations while the machine is rotating with 500 rpm during generator operation with a pure resistive load.

To summarize, the turn-to-turn fault affects the electrical quantities of the machine but the most effective way to detect the fault is to monitor the machine vibrations as it is able to detect even fault consisting of only a single to a few turns.

Fulfilment of SWPTC's goals

This project helped fulfil SWPTC's goals such as development of the electric drive train, optimizing the entire turbine and it was contributing to the wind power technology knowledge in the engineering education.

It also helps in looking into the possibilities of reducing the weight of the turbine using a more efficient electrical drive train. It also helps increasing the life span of the turbines by better knowledge of the turbine condition due to the developed diagnostics method.

Deviations from project plan

No deviations from project plan

Publications

J. Härsjö, "Modeling and analysis of PMSM with turn-to-turn fault", Ph.D. thesis, Chalmers Technical University, 2016

J. Härsjö, M. Bongiorno "Analytical and FEM Modeling of a PMSM with a turn-to-turn fault" Submitted to IET-Electric Power Applications.

J. Härsjö, M. Bongiorno "Impact of turn-to-turn faults on the electromagnetic forces in a Permanent Magnet Synchronous Machine (PMSM)" Submitted to IET-Electric Power Applications.

J. Härsjö, M. Bongiorno, "Modeling and harmonic analysis of a permanent magnet synchronous machine with turn-to-turn fault", 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), 8-10 Sept. 2015, Geneva, Switzerland

External activities

The Ph.D. student was on parental leave three months, resulting a short extension of the project time table.