Software for Torsional Vibration of Machinery Trains with Variable Frequency Drive (VFD) Motors and for Lateral Motor Force Prediction

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INTRODUCTION and JUSTIFICATION

Variable frequency drives (VFDs) and motors are widely used in industry for its relative low cost and wide speed range. However, it may induce torsional vibration problem in rotating machinery trains (Fig. 1 motor shaft crack in Ref. [1]) due to the rich harmonics in motor torques from the PWM switching. The motor torque harmonics due to VFD are hard to predict because they vary with PWM switching frequency and motor operating speed. Thus, to accurately predict the mechanical vibration, it is required to model the entire machinery train with coupled electrical and mechanical fields, including power source, power inverter, VFD controller, motor and mechanical system (Fig. 2 Entire machinery train driven by VFD motor).

DELIVERABLES

The ultimate objective of this project is to develop user friendly VFD machinery train simulation software in stand-alone code (C++ or Fortran) and integrate this into XLTRC2 for torsional and lateral vibration, stress and life prediction incorporating the following features: open-loop and closed-loop control for both synchronous and induction motors, multi-level inverters, long power cables and dv/dt filter effects, motor air gap fluctuation (motor negative and tangential cross-coupled stiffness), electrical fault condition simulation, torsional-lateral coupling, gear backlash effect, etc. Also develop software to predict lateral forces and stiffnesses (radial and tangential) due to eccentric motor rotor.

The proposed work to be finished in May 2015 based on previous work done includes the following.

1) Stand-Alone VFD Simulation Software Development
   - Add arbitrary drive torque definitions (time history, or functions of time or functions of speed) for any node number
   - Add animated illustration of mode shape
   - Add torsional steady state response (torque/stress vs. speed) analysis with user defined excitation.
   - Add additional methods for life prediction, such as nominal mean stress theory and residual mean stress theory.
   - Add nonlinear mechanical component (Holset coupling).
   - Add gear teeth fatigue prediction.
   - Add long power cable model with dv/dt filter, which can induce voltage spike (Fig. 3) at motor side and cause insulation and bearing current.
   - Add fault condition analysis for corresponding torsional vibration responses, including 2-phase/3-phase short/open circuit transient analysis and voltage unbalance analysis, which can induce torsional vibrations and the coupling/drive train components have to be sized accordingly.
   - Add steady state analysis with ideal voltage input to skip long transient simulation.
   - Add user defined initial condition for both electrical and mechanical systems.
   - Add mechanical database (library) of parameter values, including common material properties and stress limits.
   - Add electrical database (library) of parameter values, including general motor parameters for different HP rating.
   - Output all results in Excel for user’s own analysis, including angular velocity/displacement, lateral motion and motor torques.
   - Convert code to Fortran and write a subroutine of the electrical system to fully integrate it into XLTRC-2.
   - Collaborate with TRC members on field study to test and verify simulation model.

2) Cross-Coupled Stiffness Estimation for Motor Eccentricity
   - Estimate the cross-coupled tangential force based on the equivalent magnetic circuit model developed in TRC year 2013-2014.
   - Calculate equivalent cross-coupled stiffness.
• Develop stand-alone code with Excel user interface.
• Compare results from analytical model and finite element method (Ansoft Maxwell, TRC year 2012-2013)
• Model machinery train with motor eccentricity and coupled torsional-lateral motion to investigate the influence of dynamic eccentricity on coupled torsional - lateral critical speeds.
• Integrate code into XLTRC2

(3) **Stand-Alone Code for Finite Element Modeling of Motor with Motor Temperature Determination**
- Stand-alone code, no MATLAB required.
- 3D finite element modeling to determine motor parameters more accurately than from Name Plate approach estimate
- Including eddy current
- Capability for eccentric rotor and mechanical system modeling

(4) **Bearlingless Motor**
- Bearingless motor drives are being used in industry and employ intentionally unsymmetrical windings for providing levitation forces.
- Provide simple model for bearlingless motor with asymmetrical winding configuration
- Calculate magnetic torque, lateral force and damping

**COST**
1 PhD Student, 12 months $2,200/mo. Salary, $187/mo. Insurance, 2.3% Fringe on salary, approx. $9000 Tuition and Fees
Total: $38,500

**STATUS OF CURRENT WORK**
In the past TRC years, the following work has been finished.

(1) **Stand-Alone VFD Simulation Software**
- Stand-alone code with Excel user interface (Fig. 4). Matlab NOT Required to run code.
- Torque internally generated by code in motor model or specified by user vs. time.
- Internal modeled motor drive system with ideal DC bus and power switches.
- Induction motor modeling with open-loop control (constant Volts/Hertz, line-start and soft-start) and closed-loop control (field orientation and direct torque).
- Synchronous motor modeling with open-loop control (constant Volts/Hertz, line-start and soft-start) and closed-loop control (vector control).
- Mechanical system code with torsional model and torsional-lateral coupled model, including unlimited multiple shafts, multiple gears, multiple coupling flanges, proportional shaft internal damping, concentrated in-line and ground referenced damping.
- Gear backlash model included, with or without impact damping.
- Load torque specification for any node as a cubic function of node angular velocity.
- Shear stress vs. time data output in Excel for user to implement their own life estimation approaches.
- Several examples provided to illustrate the use of the software.

(2) **Negative Stiffness Estimation due to Motor Rotor Eccentricity**
- Modeled motor magnetic field with equivalent magnetic circuit model (Fig. 5).
- Motor operating condition estimated by user defined supplied voltage and power output.
- Radial magnetic force and corresponding negative stiffness calculated using Maxwell stress tensor method.
- Stand-alone code with Excel user interface developed.
- Verified by comparing results with Ansys finite element model (Fig. 6).
- Radial magnetic force vs. eccentricity, radial negative stiffness vs. motor eccentricity output in Excel (Fig. 7).