Redundant Drive with Direct Torque Control (DTC) and Dual-Star Synchronous Machine, Simulations and Verification

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Keywords

«Adjustable speed drive», «Control of Drive», «Multiphase drive», «Voltage Source Inverter (VSI)»

Abstract

The performance of a drive and the quality of torque control in DTC depend on the accuracy of the estimation of flux linkage. For applications with dual-star machine each stator winding is supplied by its own inverter and the adequate stator fluxes are built. The full redundant drive is the latest development of ABB drives based on the DTC control platform. In the paper the motor model for a dual-star synchronous machine is discussed. Based on simulations with the Simulink/Matlab model of the redundant drive the operation of the drive was confirmed. Further, the concept was verified with a 1 MW motor and two ACS6000 converters in laboratory environment.

Introduction

Most applications require high levels of availability from an electric drive system. Especially in electric ship propulsion, where availability becomes safety critical. Due to economical reasons, redundancy by multiplying the number of complete propulsion systems in one vessel is not preferred. Just adding redundancy to the power part of the frequency converter is no solution either, since the small increase in reliability is consumed again by additional complexity [11]. The optimal set-up is composed of one propeller (marine propulsion only as example) with one electric motor, having several galvanically isolated winding systems, each fed by one converter. Commonly referred to as "full redundant variable speed drive", this solution has no single point of failure in the electric nor in the auxiliary systems, while even allowing on-service repair and maintenance.
It consists of:

- two independent frequency converters with their own auxiliary systems (e.g. ACS6000 product)
- two independent control units, both controlling their own converter.
- dual-stator star 3-phase windings synchronous motor construction. Each of the inverters supplies one of the stator star windings.

The full redundant drive essentially acts like motors with coupled shafts (Figure 1). By placing the winding systems onto the same stator iron, they start building and using the same flux, while individual torque control remains the same. The two driving inverters, which are based on standard products, could get the torque reference from upper control or they are arranged in Master-Follower configuration, in which the Master drive operates in speed control mode and creates the torque reference. The Follower drive gets the torque reference from the Master and controls independently its own inverter. In case of one failure the drive continues operation with only one of the two windings supplied. The role of Master can be allocated to both drives.
This paper describes the general vector equations for a dual-stator synchronous motor. Based on the equations the equivalent circuit is drawn. In comparison with 3-phase motor equivalent circuit there is

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one additional leakage inductance (mutual inductance) which represents the interactions between the two stator windings. Electromagnetic torque is contributed with the help of two stator currents and fluxes [7], [8], [9]. As a characteristic of machines with winding systems phase shifted by 30 degrees against each other, control will have to deal with the fact, that the flux components of k=6*n +/- 1 (n odd) disappears in the airgap.

The conventional Master/Follower typical application utilises two motors mechanically coupled and the full redundant solution is applied with the motor YY30 (Figure 1).

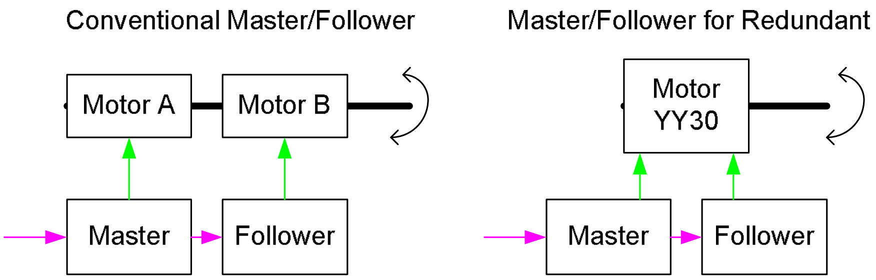

Fig. 1. Conventional Master/Follower and Master/Follower for Redundant drive with YY30 motor

Dual-Star Three Phase Synchronous Machine

The knowledge on harmonic behaviour in electrical machines is described by many authors and machine designers [1], [2], [8], [10]. The classical approach is based on computation using analytical methods: first the permeance waves are defined, then mmf-waves due to rotor and stator currents are calculated. The airgap flux density waves are obtained with interactions between permeance harmonics and stator and rotor mmf-waves. The physics behind the interactions phenomena is rather complicated and the harmonic content depends on the machine construction. The new tools using Finite Element Methods (FEM) improve accuracy of analytical methods. The FEM is used to compute the magnetic field distribution. With Fourier analysis one can compute orders, amplitudes and phases of the most significant harmonics in the flux density in the air-gap. With the help of combined analytical and FEM approaches the field harmonics, forces, noise and additional losses can be calculated [10].

In the article the topic of the space harmonic generation is not discussed. However the effect from space harmonics cannot be neglected in modeling of dual star synchronous machines with a phase shift of 30 degree.

The field harmonics from periodic air gap variation can be described by additional voltages in the stator windings, or by additional fluxes in the rotor oriented frame. The approach used in the simulations utilizes additional voltage harmonics defined from the back-emf measurements.

The vector diagram of dual-star salient pole synchronous motor with 3-phase windings in the stator is presented in Figure 2.

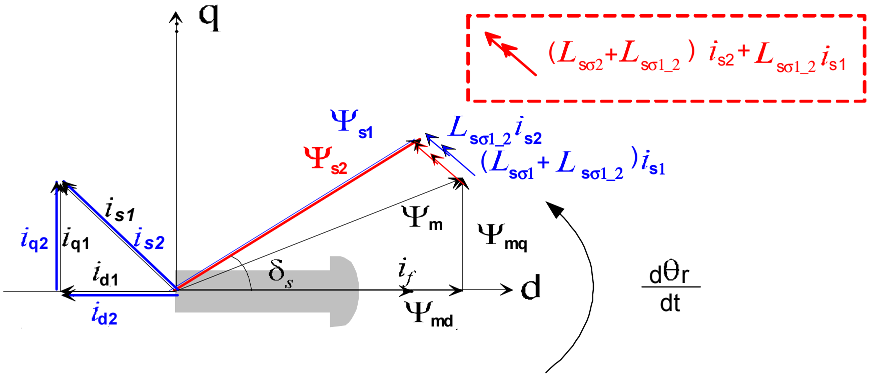

Fig. 2: Vector diagram-dual star synchronous motor in a rotor oriented reference frame

The rotor is rotating at angular velocity $\omega_R = \frac{d\theta_R}{dt}$, where θ_R is the angle between the rotor and the stationary reference frame. The load angle δ_S is defined between the stator flux and the coordinate axis **d**.

Dual-star synchronous motor equivalent circuit

The schematic of dual-star synchronous motor with 3-phase windings in the stator and with 30 electrical degrees phase shift is presented in Figure 3.

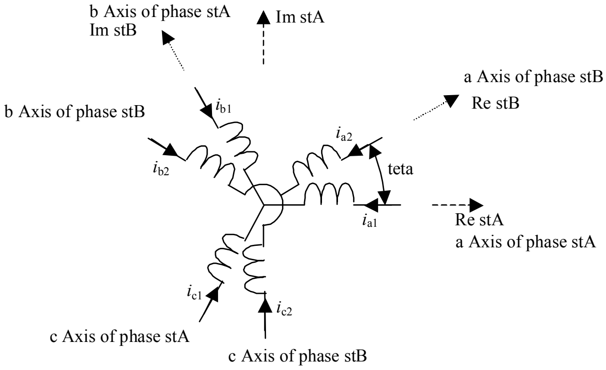

Fig. 3: Schematic of the dual-star three phase stator winding with teta=30 degrees phase shift

With the flux and voltage equations of the dual-three phase synchronous machine [5],[7],[9] the equivalent circuit can be derived for direct and quadrature axis. (Figure 4, 5).

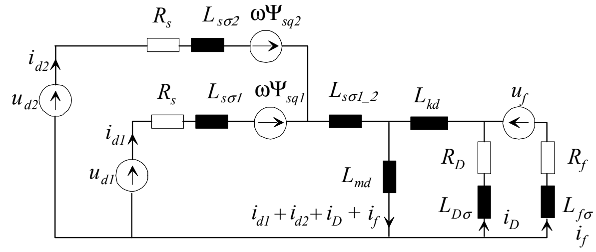

Fig. 4: Direct axis equivalent circuit of a dual three-phase synchronous motor

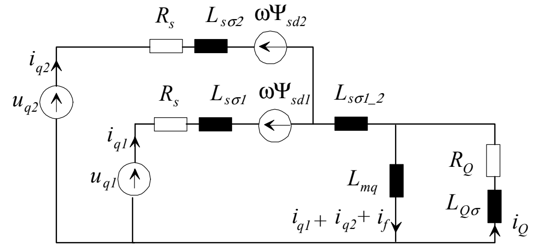

Fig. 5. Quadrature axis equivalent circuit of a dual three-phase synchronous motor

Flux linkage equations:

The flux direct and quadrature matrix (1) can be expressed:

$$\begin{bmatrix}\Psi_{sd1}\\ \Psi_{sd2}\\ \Psi_{D}\\ \Psi_{f}\end{bmatrix}=\begin{bmatrix} xsd1 & xsd1\_2 & xmd & xmd\\ xsd1\_2 & xsd2 & xmd & xmd\\ xmd & xmd & xD & xfD\\ xmd & xmd & xfD & xf\end{bmatrix}*\begin{bmatrix}i_{d1}\\ i_{d2}\\ i_{D}\\ i_{f}\end{bmatrix}\qquad \begin{bmatrix}\Psi_{sg1}\\ \Psi_{sq2}\\ \Psi_{Q}\end{bmatrix}=\begin{bmatrix} xsq1 & xsq1\_2 & xmq\\ xsq1\_2 & xsq2 & xmq\\ xmq & xmq & xQ\end{bmatrix}*\begin{bmatrix}i_{sq1}\\ i_{sq2}\\ i_{Q}\end{bmatrix}\quad (1)$$

The current direct and quadrature matrices (2) could be calculated from inverse of inductance matrices and flux components.

$$\begin{bmatrix}i_{d1}\\ i_{d2}\\ i_{D}\\ i_{f}\end{bmatrix}=\left[Ld^{-1}\right]*\begin{bmatrix}\Psi_{sd1}\\ \Psi_{sd2}\\ \Psi_{D}\\ \Psi_{f}\end{bmatrix}\qquad \begin{bmatrix}i_{q1}\\ i_{q2}\\ i_{Q}\end{bmatrix}=\left[Lq^{-1}\right]*\begin{bmatrix}\Psi_{sq1}\\ \Psi_{sq2}\\ \Psi_{Q}\end{bmatrix}\qquad (2)$$

Voltage equations

Stator voltage equations -d-, -q-, components (3), (4):

$$u_{d1}=R_s i_{d1}+\frac{d\Psi_{sd1}}{dt}-\omega_r\Psi_{sq1}\qquad u_{d2}=R_s i_{d2}+\frac{d\Psi_{sd2}}{dt}-\omega_r\Psi_{sq2}\qquad (3)$$

$$u_{q1}=R_s i_{q1}+\frac{d\Psi_{sq1}}{dt}+\omega_r\Psi_{sd1}\,.\qquad u_{q2}=R_s i_{q2}+\frac{d\Psi_{sq2}}{dt}+\omega_r\Psi_{sd2}\qquad (4)$$

Damper winding voltage equations (5):

$$u_D=0=R_D i_D+\frac{d\Psi_D}{dt}\qquad u_Q=0=R_Q i_Q+\frac{d\Psi_Q}{dt}\qquad (5)$$

Magnetizing voltage equation (6):

$$u_f=R_f i_f+\frac{d\Psi_f}{dt}\qquad (6)$$

Electromechanical torque equation

$$t_e=\frac{3}{2}p\left(\Psi_{sd1}i_{q1}-\Psi_{sq1}i_{d1}+\Psi_{sd2}i_{q2}-\Psi_{sq2}i_{d2}\right)\qquad (7)$$

where p is the number of pole pairs

Dual-star synchronous motor equivalent circuit for harmonics of order k=6*n +/-1, (n odd)

The following describes the main reasons for the k=6*n+/-1 (n=1,3,5,…) harmonics in the stator currents of YY30 motors:

- **Effects from the machine construction**: non sinusoidal air-gap flux distribution due to stator and rotor windings in slots and due to the pole shape. These harmonics can be calculated with FEM or measured from back-emf.
- **Effects from the inverter:** modulation around full voltage uses voltage vectors with small contents of 5th and 7th components

Both above reasons for the presence of 6*n+/-1 harmonics in YY30 machines and the fact that the impedance for those components is low have an influence on the increased amount of 5th and 7th components in stator currents.

In the ideal case these harmonics do not contribute to the air-gap flux. The approximate circuit for harmonic current calculation can be simplified to stator resistance and stray inductance since the magnetizing reactance is much bigger then the leakage reactance (Figure 6).

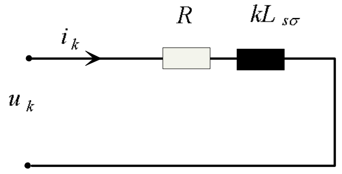

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Fig. 6. Equivalent circuit for k=6*n +/-1 harmonic currents (n=1,3,5,…)

Adaptive Motor Model for DTC Drive with Dual-star Synchronous Motor

To be able to perform control on an electric motor, the controller must be able to accurately calculate or measure the actual values of the stator or rotor magnetic flux and the airgap torque. When these actual values are known, the controller can control the inverter switches in a way that the reference values are reached.

The control system demands for an accurate motor model. The adaptive motor model for DTC drives with dual-star synchronous machines is presented in the Figure 7. It consists of parts related to the own drive (index 1- called Master) and inputs from the second drive (index 2- called Follower).

The stator flux linkage estimate is calculated with the voltage model. The inputs to the voltage model are switching positions and the measured intermediate voltages. The flux calculated from the voltage integration is corrected with resistive losses and integration errors. DTC controls flux within hysteresis bands [4], [6].

The measured or estimated phase currents are transformed to quadrature components. The inputs to the current model are the measured or estimated rotor angle and the excitation current. In the current model the damper winding currents are estimated and the inductance parameters are updated based on the operating point.

The calculation is performed in rotor coordinates. A difference between the stator flux vector of the voltage model and the stator flux vector of the current model is calculated and the result is used for flux correction.

For dual-star motors there is an interaction between the two stator windings and both stator currents contribute to the flux linkage in each of the stator stars. In both inverters the current model calculates stator flux linkages with the help of both stator currents, rotor position and inductance parameters. The torque is calculated with the help of the cross product of stator current and stator flux. In each of the inverters the torque related to half of the motor current is estimated. Both motor windings contribute to the torque on the motor shaft. (see equation. 7)

Minimizing harmonic components from stator currents with correction algorithm

With the YY30 connection we will cancel the sixth harmonic torque pulsation, or minimize it in comparison to a machine with single stator winding. However the disadvantage is that in such a topology the fifth and seventh harmonic impedances are very small, which causes high fifth and seventh harmonic components in stator winding currents, even when no or small harmonic components are present in the voltage.

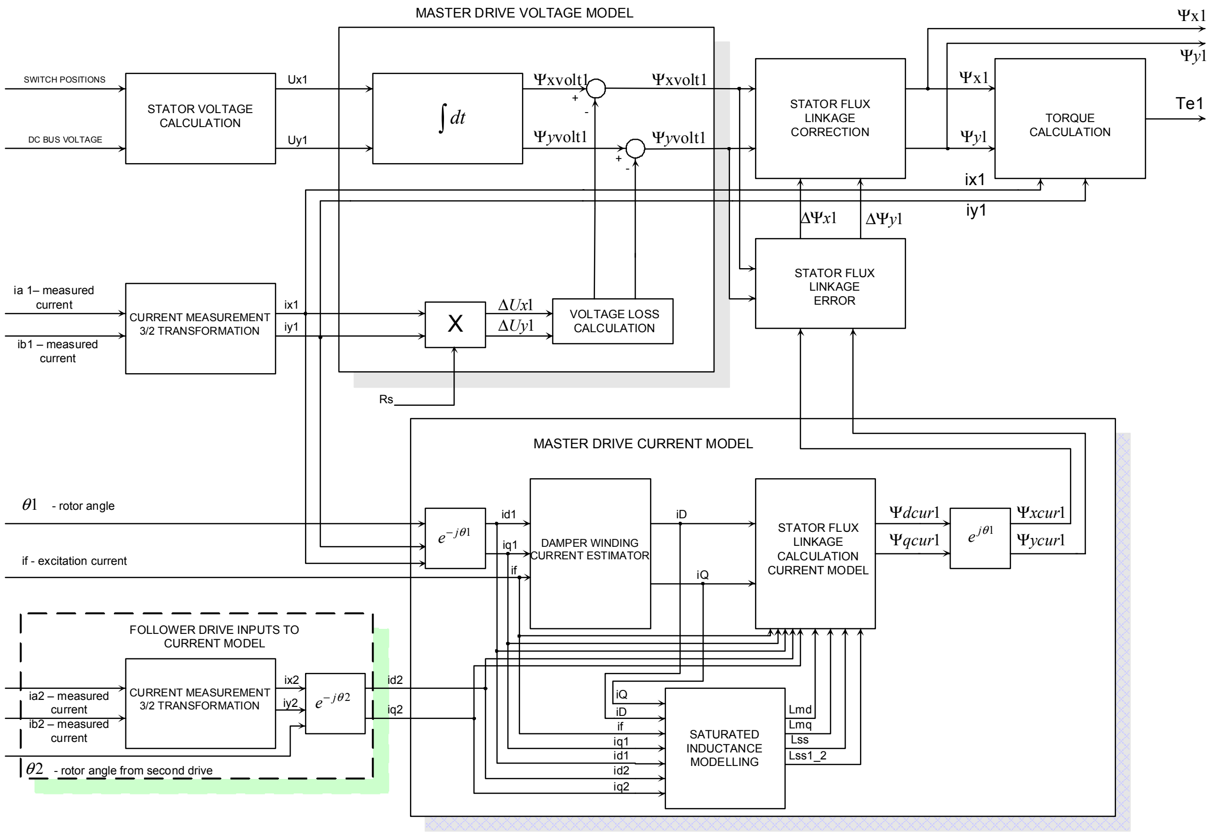

Fig. 7. Adaptive Motor Model for DTC Drive

The approach for minimizing or controlling the harmonics of order k=6*n+/- 1 (n = 1, 3, 5,…) components in the stator currents is based on modifying the output voltage of the converter in order to affect these harmonics. In the below example the adaptation algorithm, which has as input the difference between the stator flux vector of the voltage model and the stator flux vector of the current model, is used and the correction term is added to the flux reference. The corrected flux reference is an input to hysteresis control of flux (Figure 8).

- stator flux linkage error is defined in equation (8)

$$[\Delta\Psi s]=[\Delta\Psi sx \quad \Delta\Psi sy] \tag{8}$$

Flux difference in the estimated x direction is used only - $\Psi\varepsilon$

$$\Psi\varepsilon=[1 \quad 0]*\begin{bmatrix}\Delta\psi_{sx}\\ \Delta\psi_{sy}\end{bmatrix} \tag{9}$$

The correction algorithm is based on the knowledge of sixth harmonic in the rotor oriented frame. In the flux, which is calculated in rotor coordinates, we could observe the sixth harmonic pulsations. DTC controls flux with hysteresis control, and the reference is a circle. In case of presence of 5th, 7th…harmonic components the real flux in the machine is not a pure circle, but is deformed with 6th harmonic.

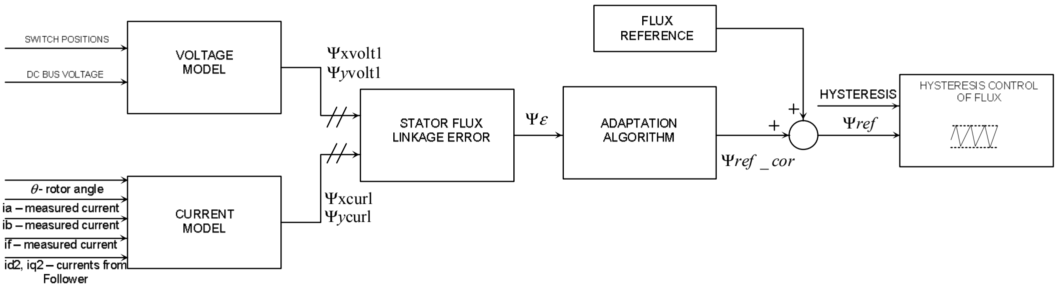

Fig. 8. Correction algorithm with additions to flux reference

Simulink Model of Drive with Dual - Star Three Phase Synchronous Machine

In the Matlab/Simulink model each three-level inverter is fed from a constant DC voltage source and the switching module is modelled as a set of ideal switches, which are controlled by direct torque control (DTC) algorithm. The implemented control structure includes models of: full modulator, motor model and motor control main functions. The simulation of the converter model is executed on several time levels according to the real application (ACS6000), (Figure 9).

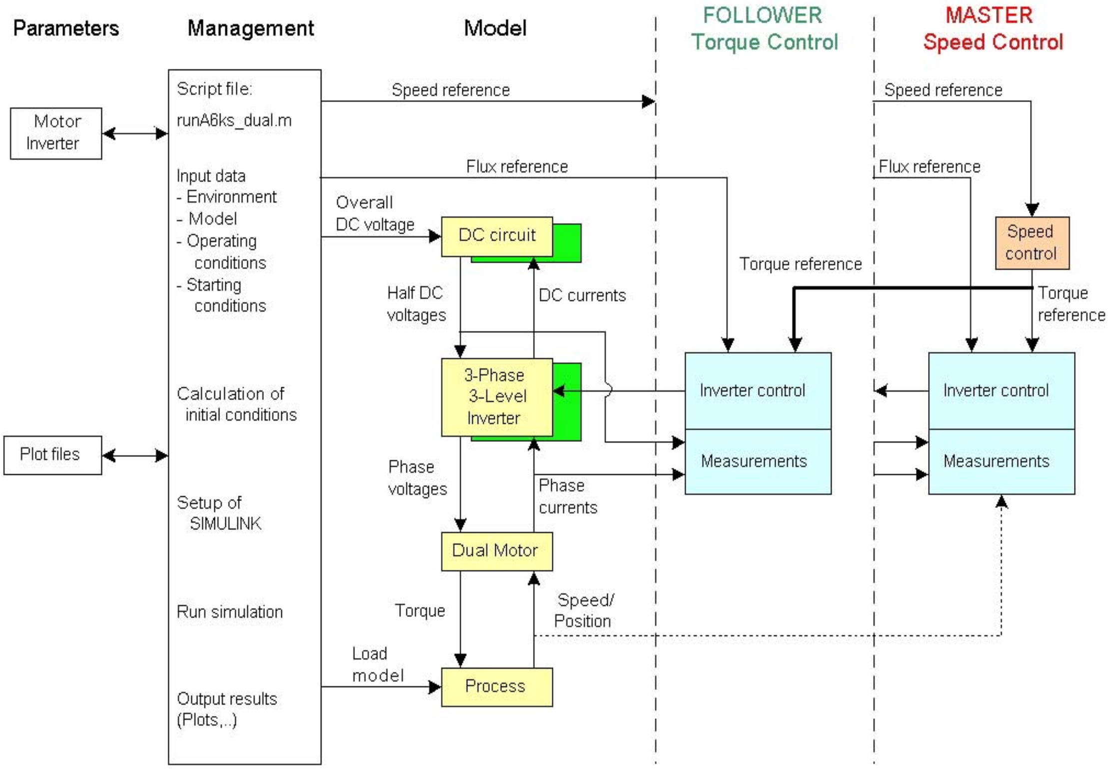

Fig. 9. Redundant Drive Simulator

Simulation and Measurement Results

Simulation results

The steady-state operation of the drive was simulated at 10 rpm and 10% of load. Switching frequency, phase currents and fluxes in both drives are presented in Figures 10a, 10b, where the effect of parasitic harmonics is the best illustrated.

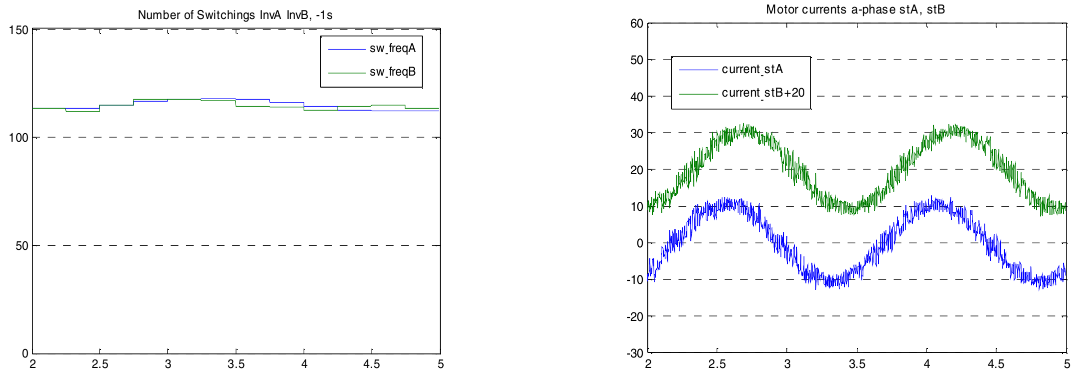

Fig. 10.a) Switching freq (Hz) in inverters InvA, InvB b) Motor phase currents Is_a1, Is_a2+20%offset

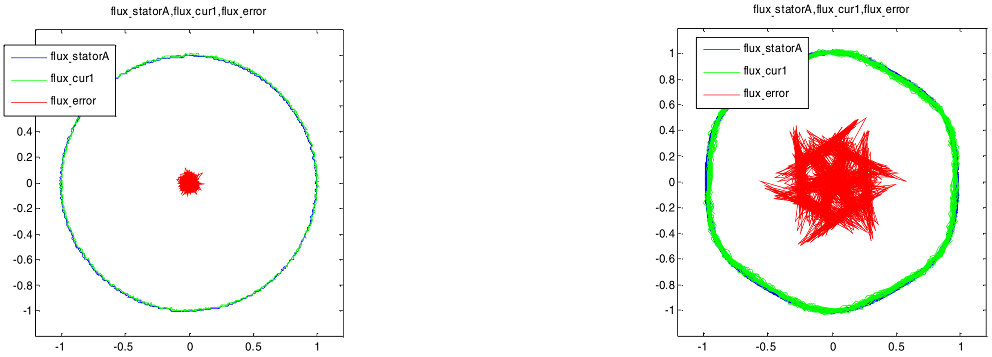

Fig. 11.a) speed =10 rpm, flux_statorA, flux_cur1-flux current model, flux_error b)speed=225 rpm flux_statorA, flux_cur1-flux current model, flux_error

The steady-state operation of the drive was simulated at rated speed with rated load. The currents in statorA and statorB are presented in Figure 12a without error correction and in Figure 12b with flux error correction applied to flux reference.

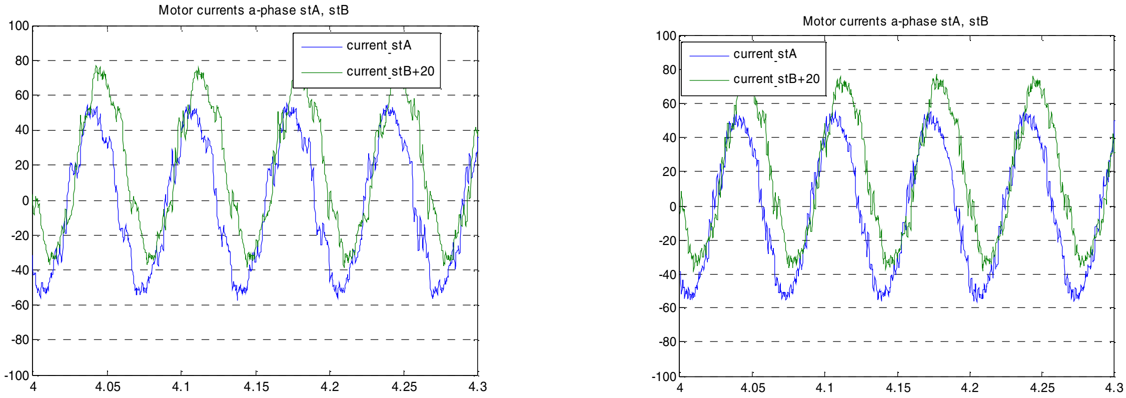

Fig. 12.a) phase current in statorA and statorB+20% offset without flux correction, b) with flux correction applied to flux reference

Measurement results

The functionality of the redundant drive concept was tested with measurements in laboratory with test motor (for machine data see Appendix 1).

In Figure 13.a- the operation is presented when both drives were running with speed 10 rpm and 10% of rated load. The switching frequency, motor phase currents and speed from both drives are measured. The robust operation of the whole drive was tested when one was tripping (Figure 13.b)

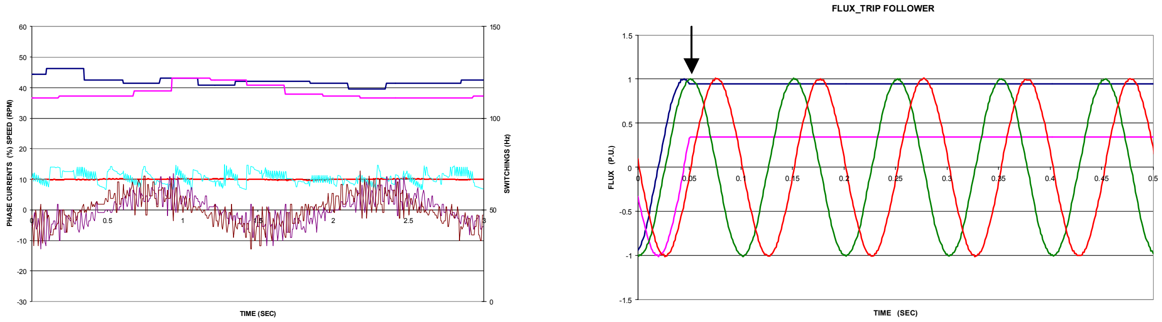

Fig. 13.a) Motor phase currents (%), motor speed (rpm), switching frequency (Hz) from both drives
Fig. 13.b) Stator flux real and imaginary components in both drives, when the other drive is tripping, At time 0.05 s Follower trips (flux trend continue) and Master remains in operation.

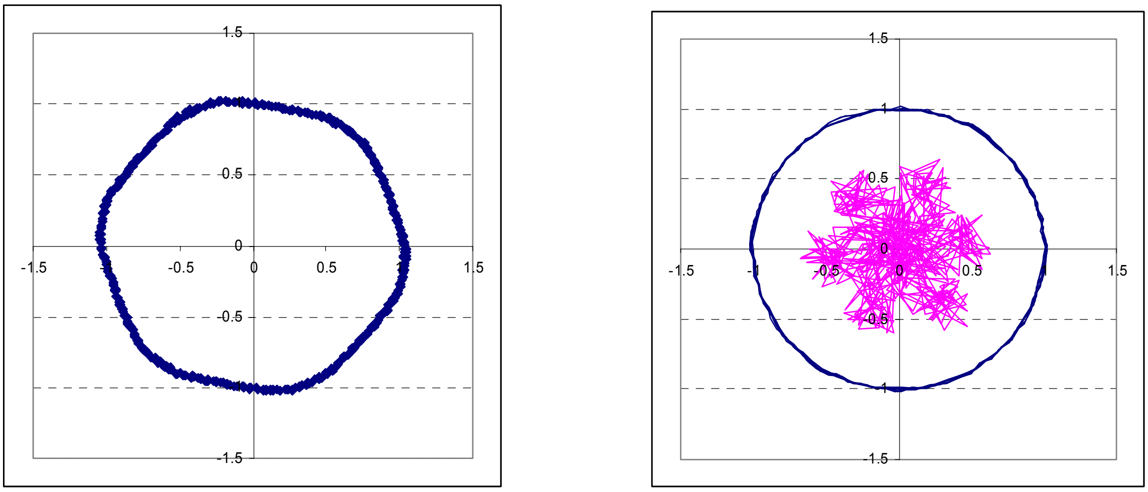

Fig. 14.a) stator flux linkage from current model, b) actual stator flux flx1,fly1 and flux error

Conclusion

In the article a redundant drive system with DTC motor control is presented and the adaptive motor model with dual-star synchronous machine is discussed. The effects of the flux density and current harmonics were investigated with the help of simulation models developed in Matlab/Simulink and the test laboratory. A simple correction algorithm is proposed. The both simulated and measured results show good agreement. The functionality of the redundant concept and the robust operation of the two independent drives were confirmed with measurements.

Especially in marine applications full redundant drives are required to assure the safe operation of the vessel even when one drive is faulted. In case of a failure in one inverter, the other one was able to continue without interruption.

References

[1] Fischer, R., “Elektrische Maschinen”, 2004,Carl Hanser Verlag, München, (in German)

[2] Alger, P., “The Nature of Induction Machines”, 1965, Gordon and Breach

[3] Jokinen, T., “Sähkököneen Synnyttämä Melu”, lectures 1980., Helsinki University of Technology, (in Finnish)

[4] Tiitinen, P., Pohjalainen, P., Lalu, J., “Next generation motor control method: Direct torque control (DTC) ” EPE Journal, vol. 5, No. 1, March 1995. pp. 14-17.

[5] Vas, P., “Vector Control of AC Machines. 1990New York, Oxford University Press. 327p

[6] Kaukonen, J., “Salient Pole Synchronous Machine Modeling in an Industrial Direct Torque Controlled Drive Application” Acta Universitatis Lappeenranta, 1999, No. 77, Finnland, Dissertation 138p.

[7] Burzanowska, H., Schroderus, P., Stulz, Ch., Lehti, M., “Novel Concept for full Redundant Drive with Direct Torque Control (DTC) and Dual-star Synchronous Machine” SPRTS-Ship Propulsion and Railway Traction Systems Conference Bologna, Italy, October 4th – 6th 2005

[8] Boloi, R., Farina, F., Griva, G., Profumo, F., Tenconi, A., “Direct Torque Control for Dual-Three Phase Induction Motor Drives” Industry Application Conference, 2004, 39th IAS Annual Meeting, 2004 IEEE

[9] Niiranen.J., “Tahtimoottorin optimointi ja käytetävyys sähkökäytössä”, 1992 Helsinki University of Technology, (in Finnish)

[10] Toader, S., “Combined analytical and finite element approach to the field harmonics and magnetic forces in synchronous machines”, ICEM 1994 Paris p.583-588

[11] Wikström, P., Terens, L.A., Kobi, H., “Reliability, Availability, and Maintainability of High-Power Variable-Speed Drive Systems”, IEEE Transactions on Industry Applications Vol 36, No 1 January/February 2000

Appendix 1

Parameters of the dual three-phase synchronous motor are referred to the stator
L_{md} = 0.1823 (H) direct axis magnetizing inductance
$L_{\mathrm{D}\sigma}$ = 0.0139 (H) direct axis damper winding leakage inductance
$L_{\mathrm{f}\sigma}$ = 0.0177 (H) magnetizing winding leakage inductance
L_{kd} = 0 damper winding and magnetizing winding leakage inductance (Canay inductance)
L_{mq} = 0.0816 (H) quadrature axis magnetizing inductance
$L_{\mathrm{Q}\sigma}$ =0.0093 (H) quadrature axis damper winding leakage inductance
$L_{\mathrm{s}\sigma 1}$ = $L_{\mathrm{s}\sigma 2}$ =0.0174 (H) statorA, statorB leakage inductance
$L_{\mathrm{s}\sigma 1\_2}$ = 0.0047 (H) statorA _statorB mutual leakage inductance
R_{s} = 0.5274 (Ω) stator resistance
R_{f} = 0.0421 (Ω) magnetizing winding resistance
R_{D} = 1.1204 (Ω) direct axis damper winding resistance
R_{Q} = 0.7510 (Ω) quadrature axis damper winding resistance
Motor data :
Nominal power = 1000 kW
Nominal voltage = 3300 V
Nominal current = 185 A
Nominal frequency = 15 Hz
Nominal speed = 225 rpm