Controlling the Dc-link Midpoint Potential in a Six-phase Motor-drive

*+Flemming Buus Bendixen, +Frede Blaabjerg, +Peter Omand Rasmussen, #Pierre Vadstrup, *Kenneth Krabbe
E-mail: fbb@vestas.com, kekr@vestas.com, fbl@iet.aau.dk, por@iet.aau.dk, pvadstrup@grundfos.com

*Vestas Wind Systems A/S, Århus, Denmark
+Aalborg University, Institute of Energy Technology, Denmark
#Grundfos Management A/S, Bjerringbro, Denmark

Abstract— **Traditionally electrical motors have three phases, but multiphase motors have shown to improve motor performance and efficiency. This paper concentrates about the control algorithm for a six-phase induction motor with third harmonic current injection. The problem is that typically a seventh inverter branch and filter inductance is needed for stabilizing the midpoint potential of the series connected dc-capacitor link. A new control strategy that pre-calculates the allowed voltage ripple and controls the motor voltage accordingly (using two standard three phase inverter modules) is suggested. With this new control strategy the seventh branch and an inductance can be saved. It also opens the possibility to use two standard three-phase inverters to supply the six-phase motor. An experimental setup is build and the theory is verified in the test case. The proposed control strategy works satisfactory. A drawback is that the voltage ripple in the midpoint increases, if a third harmonic current is injected specially at low speed, which could demand a higher voltage rating of the capacitors. Another drawback is that the higher voltage ripple will stress the capacitors hence the lifetime may be shortened.**

I. INTRODUCTION

Three-phase inverters used in adjustable speed drives are a very common configuration. A more and more discussed item is to relax the traditionally three-wire link between the motor and the inverter, to increase the performance of the motor, by using a multiphase motor drive. Different performance improvements have been demonstrated like in [1], where it is stated that using six motor phases, the motor peak torque can be increased by up to 40%, depending on the motor geometry. In [2] the torque ripple and the dc-link ripple is decreased using a six-phase motor. The efficiency of a multi-phase motor is also demonstrated to increase compared to a three-phase motor according to [3] and [4]. These improvements depend on the ability to inject odd higher harmonic components in the air-gab flux, giving an squarer wave shape of the flux density vs. position [5]. The most relevant and significant harmonic component is the third harmonic, which in a six-phase motor demands for a return path for the stator current. In a three-phase motor this will give a third harmonic torque ripple, and no extra torque. In order to avoid torque ripple a six-phase motor can be used [6].

This paper will discuss the controllability of a six-phase motor drive, where a third harmonic term is added in the current and using a return path for the current to the mid-point of the dc-link (see Fig. 1b). This has the disadvantage, compared to a seventh inverter leg (see Fig. 1a) that the load of the dc-link capacitors is uneven and may cause a non-symmetrical mean voltage across the dc-link capacitors. A new control method is proposed to stabilize the dc-link. First the basic operation of a six-phase motor is explained. Next, the new method to control the dc-link is introduced. Finally, simulations and experiments are presented to validate the method.

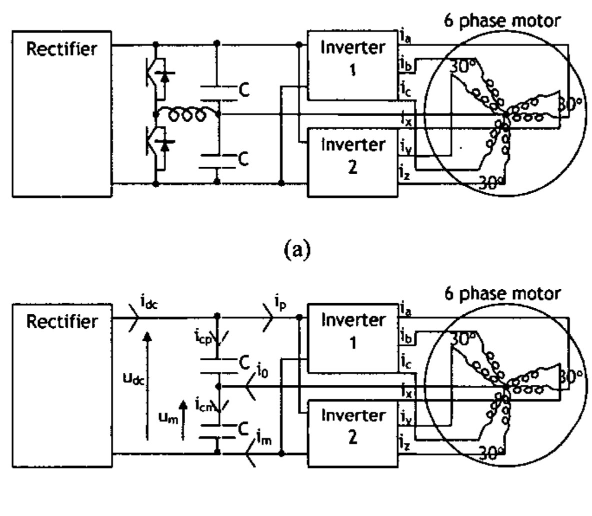

Fig. 1.: Control of a six-phase motor. (a) Two inverters with three phases and an extra branch used for voltage stabilization. (b) Two inverters with three phases. The six motor supply phases are here also used to stabilizing the voltage.

II. OPERATION OF A SIX-PHASE MOTOR DRIVE

A six-phase motor drive topology is shown on Fig. 1a, where an inverter with seven branches is used [6]. This gives the possibility to inject a third harmonic current in each phase, returning it in the neutral connection of the motor. The alternative solution is to skip the seventh branch and the inductor and control the midpoint voltage by the six other branches. The idea of transforming the abc-axis to a fixed dq-frame to improve and simplify the control algorithm can also be used in a six-phase motor just like in a three-phase motor. In the six-phase transformation matrix the third harmonic component is also taken into account.

The transformation (suggested in [6]) is shown in eq.1, where it is used to transform the currents.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \\ i_x \\ i_y \\ i_z \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & \cos\beta & 0 & 0 & \sin\beta \\ \cos(\theta-\frac{2\pi}{3}) & \sin(\theta-\frac{2\pi}{3}) & \cos\beta & 0 & 0 & \sin\beta \\ \cos(\theta+\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) & \cos\beta & 0 & 0 & \sin\beta \\ 0 & 0 & \sin\beta & \cos(\theta-\frac{\pi}{6}) & \sin(\theta-\frac{\pi}{6}) & -\cos\beta \\ 0 & 0 & \sin\beta & \cos(\theta-\frac{5\pi}{6}) & \sin(\theta-\frac{5\pi}{6}) & -\cos\beta \\ 0 & 0 & \sin\beta & \cos(\theta+\frac{\pi}{2}) & \sin(\theta+\frac{\pi}{2}) & -\cos\beta \end{bmatrix} \begin{bmatrix} i_{q1} \\ i_{d1} \\ i_{q0} \\ i_{q2} \\ i_{d2} \\ i_{d0} \end{bmatrix} \quad (1)$$

Where θ is the angular position of the electrical field, $\beta=3\theta+3\gamma$, γ is the angle between the first and third harmonic component, i_{q1}, i_{q2} i_{d1}, and i_{d2} are the q- and d-axis components for each subsystem abc (1) and xyz (2), i_{q0} and i_{d0} are the q- and d-axis current for the third harmonic current.

The current in the neutral connection i_0 can be calculated by adding all the elements in the matrix. The result after some calculation is shown in eq.2.

$$i_0(t) = \sum_{n=\{a,b,c,x,y,z\}} i_n = 3\cdot\sqrt{2}\cdot i_{q0}(t)\cdot\sin(3\cdot\theta(t)+3\cdot\gamma+\tfrac{\pi}{4}) + 3\cdot\sqrt{2}\cdot i_{d0}(t)\cdot\sin(3\cdot\theta(t)+3\cdot\gamma-\tfrac{\pi}{4}) \quad (2)$$

III. STABILIZING THE DC-LINK

In [6] it is found that the electrical potential of the dc-link midpoint (u_m in Fig. 1b) is unstable partly due to asymmetrical capacitors etc. and partly due to drift see the next section. In [6] a seventh inverter-leg is used to keep a fixed voltage. But a major disadvantage is that two standard three-phase inverter-modules are not enough. Two extra transistors with diodes and gate-drivers and an inductor are needed (Fig. 1a).

In this paper it is examined if u_m can be controlled through a more integrated motor controller and just let the potential vary according to the third harmonic current. This gives some limitations in the amplitude of the third harmonic current at very low speed because the voltage ripple may become high, limiting the applicable voltage to the motor. On the other hand the necessary voltage applied to the motor is also decreased because the induced voltage is nearly linearly dependent on the speed. Higher voltage ripple could also demand for higher voltage rating of the capacitors. It is important to note that u_m is dictated by the zero sequence current, so if i_0 has a DC value, u_m will drift towards either u_{dc} or zero. So u_m has to be measured and controlled.

B. Analysis of dynamic system with two dc-link capacitors

Considering the electric circuit in Fig. 1b it can be seen that the midpoint potential u_m depends on the current in the return path i_0. From the circuit in Fig. 1b, eq.3 can be set up:

$$u_m(t) = \frac{1}{2C}\int i_0(t)dt + \frac{u_{dc}}{2} \quad (3)$$

The current i_0 is already known from the given reference value (see eq.2), but the needed integration involve problems. The directly integrated voltage $u_{mi\ ref}$ can be calculated to:

$$u_{mi\,ref}(t) = \frac{3}{\sqrt{2}\cdot C}\int i_{q0}(t)\cdot\sin(3\cdot\theta(t)+3\cdot\gamma+\tfrac{\pi}{4})dt + \frac{3}{\sqrt{2}\cdot C}\int i_{d0}(t)\cdot\sin(3\cdot\theta(t)+3\cdot\gamma-\tfrac{\pi}{4})dt + \frac{u_{dc}}{2} \quad (4)$$

If the currents i_{d0} and i_{q0} are constant in time, the mean value of $u_{mi\ ref}$ is $u_{dc}/2$, and this is the optimal value. But if the currents are changed dynamically, the capacitor voltage tends to drift out of control, dependent on when the currents are changed.

C. New solution

A new strategy is proposed where the integration is done analytically and not online. This has the advantage that drift can be avoided. If it is assumed that the currents are constant in time, the integration can be solved. The result is shown in eq.5.

$$u_{m\,ref}(t) = \frac{-i_{q0}(t)\cdot\cos(3\cdot\theta(t)+3\cdot\gamma+\frac{\pi}{4})}{\sqrt{2}\cdot C\cdot\omega_e(t)} - \frac{i_{d0}(t)\cdot\cos(3\cdot\theta(t)+3\cdot\gamma-\frac{\pi}{4})}{\sqrt{2}\cdot C\cdot\omega_e(t)} + \frac{u_{dc\,meas}}{2} \quad (5)$$

Using that $\theta(t)=\omega_e t$ and ω_e is the angular speed of the electrical field. Here $u_{m\ ref}$ does not drift, and the mean value is as close to $\frac{1}{2}u_{dc\ meas}$ as possible. In other words the analytical solution eliminates the drift. Now this new predicted voltage $u_{m\ ref}$ can be used as a reference for the measured midpoint voltage $u_{m\ meas}$. The error signal is used in a controller and added to the reference voltages for the motor phases. The final control loop is shown in Fig. 2.

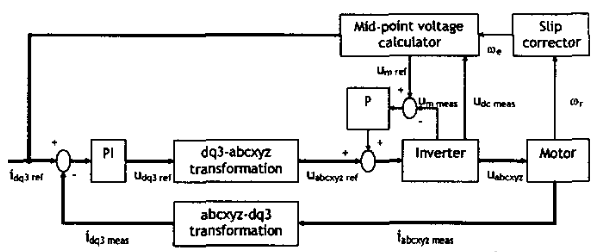

Fig. 2.: Diagram of the proposed control system for midpoint potential. The thick lines indicate six wires or six signals. The thin lines mean only one signal.

Where dq3-abcxyz and abcxyz-dq3 refers to the transformation back and forth between rotating and stationary coordinates. To control the currents six PI controllers are used. The slip corrector first calculates the motor slip speed $\omega_s = \frac{r_r}{L_m+L_{lr}}\frac{i_q}{i_d}$ like in standard vector control [7] and then the electrical field speed ω_e, from the measured motor speed ω_r, using $\omega_e = \omega_r + \omega_s$. In the mid-point voltage calculator the acceptable reference voltage is calculated using eq.5. It is important to note that the number of independent inputs to the motor is the six currents (the zero current is not independent because it is the sum of the six currents), but seven conditions (the six currents and the midpoint voltage) have to fit and be controlled. So one of the controllers has to be secondary, and small errors have to be accepted. For the midpoint controller it is therefore chosen to use a simple P-controller, which gives a small steady state error, but in simulation and practice it works well together with the six current controllers.

IV. SIMULATION RESULTS

The new control system is simulated using the current control system proposed in [6] and a high order motor model suggested in [8]. The main parameters for the system are shown in a table in appendix A. The new midpoint voltage controller is tested by supplying an artificial dc offset current of -1.4 A, that starts at the time 0.5 s. Without a midpoint controller the motor currents will not be affected (see Fig. 3) but the midpoint voltage will increase linearly, as shown in Fig. 4, until it is equal to u_{dc}, and the motor has to stop or the capacitor will fail.

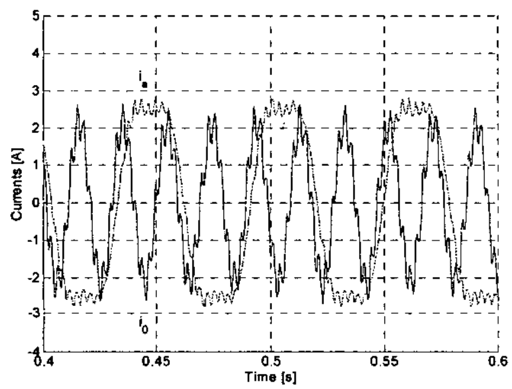

Fig. 3.: Simulation of six-phase motor drive without dc-controller. Asymmetry occurs at 0.5 s. Phase a current and zero current.

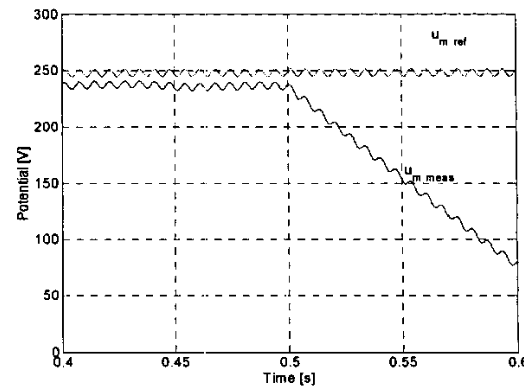

Fig. 4.: Simulation of six-phase motor drive without dc-controller. Asymmetry occurs at 0.5 s. Simulated voltages.

Using the new suggested controller, the midpoint voltage is stabilized, and the motor is able to continue to run (see Fig. 5 and Fig. 6). In the case of using the proposed control system, the controller corrects the motor currents so the motor now supplies the -1.4 A in i_0 to the disturbance (with 0.23 A dc for each phase).

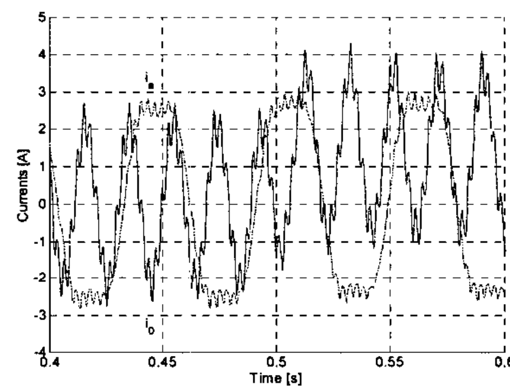

Fig. 5.: Simulation of six-phase motor drive with dc-controller. Asymmetry occurs at 0.5 s. Phase a current and zero current.

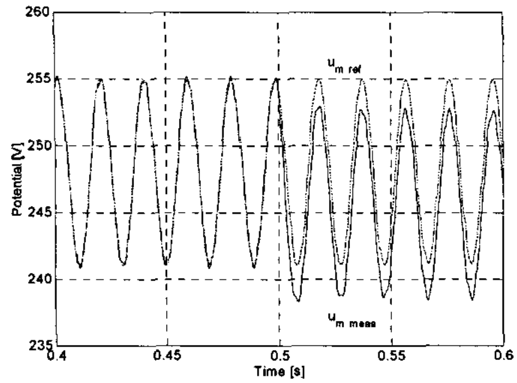

Fig. 6.: Simulation of six-phase motor drive with dc-controller. Asymmetry occurs at 0.5 s. Simulated voltages.

V. EXPERIMENTS

Two standard three-phase inverters and a special wounded six-phase induction motor are used in the test system. The test system is pictured in Fig. 7.

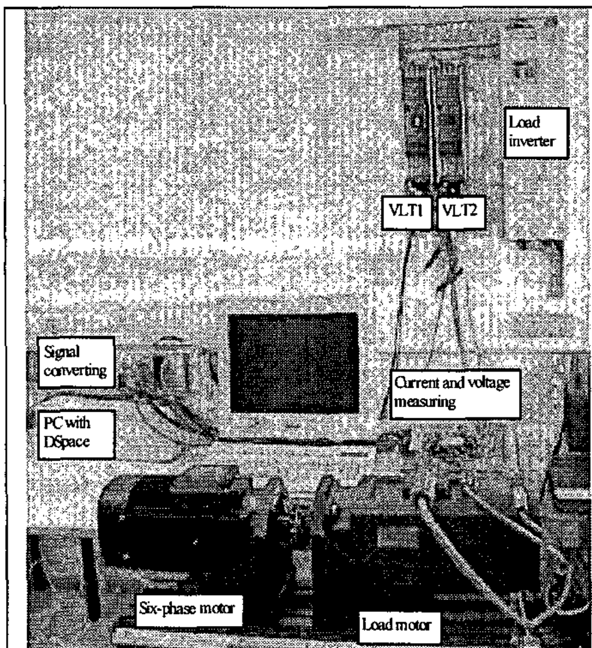

Fig. 7.: Picture of laboratory test system.

It is found that without the controller the system cannot even start, because the midpoint voltage becomes so asymmetric that the control system stops to prevent over voltage on one of the capacitors. If the midpoint controller is turned on the system starts without problems. The system is tested with nearly the same procedure as in the simulation. In practice a resistance of 177 Ω is connected across the lower capacitor u_m at the time 0.71 s and the results are shown in Fig. 8 and Fig. 9. The expected current offset i_0 is -1.4 A. In the test the motor runs 1000 rpm and it is loaded with 7.5 Nm.

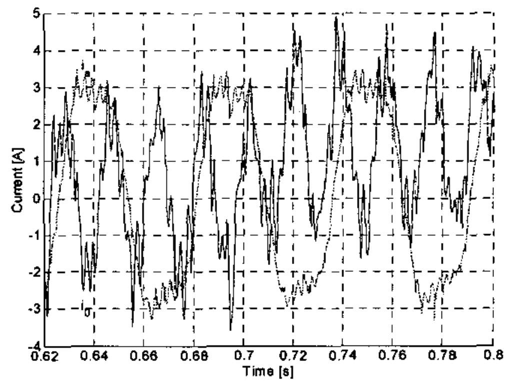

Fig. 8.: Test of six-phase motor drive with midpoint-controller. Asymmetry occurs at 0.71 s. Phase a current and zero current.

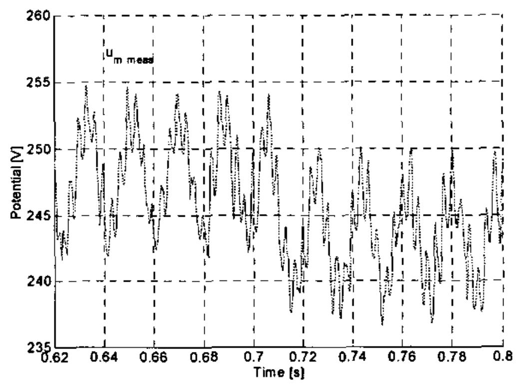

Fig. 9.: Test of six-phase motor drive with midpoint-controller. Asymmetry occurs at 0.71 s. Measured midpoint voltage $u_{m\ meas}$.

B. Comparison of simulation and experiments

The simulated and the tested currents generally fit well, both in amplitude, phase and harmonic content. The simulated and the tested voltages also fit in most aspects, but the measured voltage has a high harmonic content, which is not modeled. This could be noise in the measurements

VI. CONCLUSION

A new control method for a six-phase motor with third harmonic current injection, saving an inverter branch and an inductance, is proposed. This controller calculates an acceptable reference for the midpoint potential using a feed forward approach of the third harmonic reference current. The idea that the six other phases can be used to stabilize the midpoint potential in the capacitor link is simulated and tested in the laboratory. The new control strategy works satisfactory.

APPENDIX A

Some important characteristics for the test system are shown in the table below.

Parameter	Value
Test motor nominal torque	9.9Nm@2908RPM
Test motor shaft power	3kW
Test motor poles	2
Test motor rewound from	Grundfos MG100
Test motor active length	140mm
Test motor active OD	135mm
Inverter output power	3.1 and 4.3KVA
Inverter type	Danfoss VLT 5004
Load drive	Siemens PMSM
Maximum load torque	20Nm@4500RPM
D-Space system	1103-PPC

ACKNOWLEDGMENT

The authors would like to thank Vestas Wind Systems, Aalborg University, ATV and Grundfos Management for sponsoring the PhD project under which this article is produced.

REFERENCES

[1] R. O. C. Lyra; T. A. Lipo "Torque Density Improvement in a Six-Phase Induction Motor With Third Harmonic Current Injection." Industry Applications Conference, 2001. Thirty-Sixth IAS Annual Meeting. Conference Record of the 2001 IEEE, pp: 1779 – 1786, vol.3, 2001.

[2] V. Weisgerber. "Double-pulse inverter feeds 6-phase asynchronous motor for harmonic loss reduction". EPE Fifth European Conference on Power Electronics and Applications, 1993.

[3] Borealis Chorus motor tutorial "http://www.chorusmotors.gi/technology/motortutorial1.pdf" sited at 21/11-2003.

[4] S. Williamson. S. Smith. "Pulsating torque and losses in multiphase induction machines" IEEE Transactions on Industrial Applications, Vol. 39, No. 4, July/August 2003, pp: 986-993.

[5] H. A. Toliyat; T. A. Lipo; J. Coleman White "Analysis of concentrated winding induction machines for adjustable speed drive applications Part 2 (Motor design and performance)." IEEE Transactions on Energy Conversion, Vol. 6, No. 4, December 1991.

[6] R. O. C. Lyra. "Torque Density Improvement In A Six-Phase Induction Motor With Third Harmonic Current Injection." ph.d. thesis, University of Wisconsin – Madison. 2002.

[7] D. W. Novotny; T. A. Lipo "Vector control and dynamics of AC drives" Oxford Science publications. ISBN: 0-19-856439-2. First published 1996, pp: 232.

[8] H. A. Toliyat; T. A. Lipo; J. Coleman White "Analysis of concentrated winding induction machines for adjustable speed drive applications Part 1 (Motor analysis)." IEEE transactions on energy conversion, Vol. 6 No. 4, December 1991.