# IECON 2008: A TUTORIAL PROPOSAL

**TUTORIAL TITLE:** **Variable Speed Multiphase Drives**

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**OTHER PRESENTERS: none**

**TUTORIAL ABSTRACT:**

Although the concept of variable speed drives, based on utilization of multiphase (more than three phases) machines, dates back to the late sixties of the last century, it was not until the mid to late nineties that multiphase drives have become serious contenders for various applications. These include electric ship propulsion, locomotive traction, electric and hybrid electric vehicles, 'more-electric' aircraft, and high power industrial applications. As a consequence, there has been a substantial increase in the interest for such drive systems world-wide, resulting in a huge progress during the last ten years. This tutorial is aimed primarily at those who are not familiar with this area and it attempts to provide an introduction into the field. The tutorial is structured in six sections and it addresses in the first part the reasons for employing multiphase variable speed drives, concentrating on their advantages and shortcomings. A survey of actual and potential industrial applications is also provided in the first section and the available approaches to multiphase machine stator winding design are surveyed. The second part contains considerations related to the modelling of multiphase machines, with a multiphase induction machine taken as an example. Modelling based on the general theory of electrical machinery is covered and both machines with concentrated stator windings and machines with near-sinusoidal mmf distribution are encompassed. Models obtained in this way constitute the basics of the subsequent control system design for a multiphase variable speed drive. The third section discusses various vector control schemes (using stationary and synchronous current controllers) and direct torque control schemes (based on switching table concept and with constant switching frequency) that are nowadays available. Attainable performance is illustrated using experimental results collected from a number of five-phase and six-phase induction motor laboratory rigs. Use of additional degrees of freedom (currents), available in multiphase machines, for torque enhancement by higher stator current injection in concentrated winding machines is encompassed by this section. This is followed by the discussion of the multiphase voltage source inverter control in the fourth section. Carrier-based and space vector PWM control methods are covered in a considerable detail and numerous experimentally obtained results are used to illustrate the multiphase inverter operation (five-phase, six-phase and seven-phase two-level inverters are considered). Two further possibilities for the use of additional degrees of freedom in multiphase machines are discussed in the last two sections of the tutorial. In particular, the fifth section elaborates fault-tolerant operation. Existing scenarios for post-fault control strategy design are discussed and post-fault operation is illustrated using a five-phase induction motor as an example. The last section of the tutorial covers an alternative use of the additional degrees of freedom, namely multi-motor multiphase series-connected and parallel-connected variable speed drives with a single multiphase inverter supply and independent, fully decoupled vector control. This is applicable to machines with near-sinusoidal mmf distribution and the principles of operation are surveyed for a couple of supply phase numbers. Operation of two-motor series-connected five-phase and six-phase drives is illustrated using experimental results.

**INTENDED AUDIENCE:** The tutorial is designed for attendees with good knowledge of three-phase variable speed drives. The assumption is that the attendees will be familiar with principles of vector control, direct torque control and voltage source inverter PWM control, as applied in variable speed three-phase drives, but that they have not dealt with multiphase variable speed drives in the past and are therefore novices in this specific field. The expected knowledge level is therefore basic.

The tutorial is associated with the following topics of the conference call for papers: i) Electric Drives and Machines; ii) Power Electronics.

## THE PRESENTER – Emil Levi

**SHORT BIOGRAPHY:** The presenter is, since 2000, Professor of Electric Machines and Drives at Liverpool John Moores University (UK), with over 25 years of research experience in the electric machines, variable speed drives and power electronics areas. His publication record consists of more than 240 full journal and conference papers and includes 70 published and accepted journal papers in Science Citation Index source journals (more than 40 of which are in IEEE/IEE/IET journals). The presenter has been conducting research in the proposed tutorial area since 2001 and the following is the brief summary of the data pertinent to this proposal.

***Guest Editorships:***

I. Special Section on "Multiphase Machines and Drives," *IEEE Trans. on Industrial Electronics*, vol. 55, no. 5, May 2008.

II. Special Issue on "Multiphase and Multi-Motor Drive Systems," *EPE Journal,* vol. 14, no. 3, June-August 2004.

***Major research projects:***

I. "Parallel-connected multi-drive systems with reduced number of inverter legs and independent vector control," EP/C007395/1 (Principal Investigator), 01 December 2005 – 30 November 2007, £ 209,635.

II. "A new concept for multidrive systems: Independent control of a set of motors supplied from a common inverter," GR/R64452/01 (Principal Investigator), 01 June 2002 – 31 May 2005, £ 201,589.

***Major collaborators in multiphase drives area:***

Texas A&M University, TX (Prof. H.A.Toliyat)
Politenico di Torino, Italy (Prof. F.Profumo, Dr. R.Bojoi)
The University of Manchester, UK (Prof. S.Williamson)
University of Seville, Spain (Dr. M.J.Duran)
University of Bologna, Italy (Prof. G.Serra, Dr. G.Grandi, Prof. D.Casadei, et al)
University of Lille, France (Dr. E.Semail)
Companies: Semikron – UK, MOOG – Italy, Verteco – Finland, Infineon – Germany, ABB - Sweden

***Journal tutorial/review papers:***

1. E.Levi; Multiphase electric machines for variable speed applications, *IEEE Trans. on Industrial Electronics*, vol. 55, no. 5, May 2008.
2. E.Levi, R.Bojoi, F.Profumo, H.A.Toliyat, S.Williamson; Multiphase induction motor drives – A technology status review, *IET – Electric Power Applications*, vol. 1, no. 4, 2007, pp. 489-516.

***SCI journal papers (published and accepted; multiphase drives area only):***

3. E.Levi, M.Jones, S.N.Vukosavic, H.A.Toliyat; Steady state modelling of series-connected five-phase and six-phase two-motor drives, *IEEE Trans. on Industry Applications,* vol. 44, 2008.
4. E.Levi, D,Dujic, M.Jones, G.Grandi; Analytical determination of DC-bus utilization limits in multi-phase VSI supplied AC drives, *IEEE Trans. on Energy Conversion,* vol. 23, 2008.
5. D.Casadei, D.Dujić, E.Levi, G.Serra, A.Tani, L.Zarri; General modulation strategy for seven-phase inverters with independent control of multiple voltage space vectors, *IEEE Trans. on Industrial Electronics*, vol. 55, no. 5, May 2008.
6. D.Dujic, G.Grandi, M.Jones, E.Levi; A space vector PWM scheme for multi-frequency output voltage generation with multi-phase voltage source inverters, *IEEE Trans. on Industrial Electronics,* vol. 55, no. 5, 2008.
7. M.Duran, S.Toral, F.Barrero, E.Levi; Real-time implementation of multi-dimensional five-phase space vector pulse-width modulation, *Electronics Letters*, vol. 43, no. 17, 16th August 2007, pp. 949-950.
8. E.Levi, M.Jones, S.N.Vukosavic, A.Iqbal, H.A.Toliyat; Modelling, control and experimental investigation of a five-phase series-connected two-motor drive with single inverter supply, *IEEE Trans. on Industrial Electronics,* vol. 54, no. 3, 2007, pp. 1504-1516.
9. E.Levi, M.Jones, A.Iqbal, S.N.Vukosavic, H.A.Toliyat; An induction machine / Syn-Rel two-motor five-phase series-connected drive, *IEEE Trans. on Energy Conversion,* vol. 22, no. 2, 2007, pp. 281-289.

10. D.Dujic, A.Iqbal, E.Levi; A space vector PWM technique for symmetrical six-phase voltage source inverters, *European Power Electronics & Drives (EPE) Journal*, vol. 17, no. 1, 2007, pp. 24-32.
11. M.Jones, E.Levi; Series connected quasi-six phase two-motor drives with independent control, *Mathematics and Computers in Simulation (Transactions of IMACS),* vol. 71, no. 4-6, 2006, pp. 415-424.
12. A.Iqbal, E.Levi; Space vector PWM techniques for sinusoidal output voltage generation with a five-phase voltage source inverter, *Electric Power Components and Systems,* vol. 34, no. 2, 2006, pp. 119-140.
13. E.Levi, M.Jones, S.N.Vukosavic; A series-connected two-motor six-phase drive with induction and permanent magnet machines, *IEEE Trans. on Energy Conversion,* vol. 21, no. 1, 2006, pp. 121-129.
14. R.Bojoi, E.Levi, F.Farina, A.Tenconi, F.Profumo; Dual three-phase induction motor drive with digital current control in the stationary reference frame, *IEE Proc. – Electrical Power Applications,* vol. 153, no. 1, pp. 129-139, 2006.
15. M.Jones, S.N.Vukosavic, E.Levi, A.Iqbal; A six-phase series-connected two-motor drive with decoupled dynamic control, *IEEE Trans. on Industry Applications,* vol. 41, no. 4, 2005, pp. 1056-1066.
16. S.N.Vukosavic, M.Jones, E.Levi, J.Varga; Rotor flux oriented control of a symmetrical six-phase induction machine, *Electric Power Systems Research,* vol. 75, no. 2-3, 2005, pp. 142-152.
17. M.Jones, E.Levi, A.Iqbal; Vector control of a five-phase series-connected two-motor drive using synchronous current controllers, *Electric Power Components and Systems,* vol. 33, no. 4, 2005, pp. 411-430.
18. E.Levi, S.N.Vukosavic, M.Jones; Vector control schemes for series-connected six-phase two-motor drive systems, *IEE Proc. – Electric Power Applications,* vol. 152, no. 2, 2005, pp. 226-238.
19. E.Levi, M.Jones, S.N.Vukosavic, H.A.Toliyat; Operating principles of a novel multi-phase multi-motor vector controlled drive, *IEEE Trans. on Energy Conversion,* vol. 19, no. 3, 2004, pp. 508-517.
20. E.Levi, M.Jones, S.N.Vukosavic, H.A.Toliyat; A novel concept of a multiphase, multi-motor vector controlled drive system supplied from a single voltage source inverter, *IEEE Trans. on Power Electronics,* vol. 19, no. 2, 2004, pp. 320-335.
21. E.Levi, M.Jones, S.N.Vukosavic; Even-phase multi-motor vector controlled drive with single inverter supply and series connection of stator windings, *IEE Proc. – Electric Power Applications*, vol. 150, no. 5, 2003, pp. 580-590.

***Refereed other journal papers:***

22. E.Levi, M.Jones, S.N.Vukosavic, H.A.Toliyat; A five-phase two-machine vector controlled induction motor drive supplied from a single inverter, *European Power Electronics & Drives Journal*, vol. 14, no. 3, 2004, pp. 38-48.
23. E.Levi, A.Iqbal, S.N.Vukosavic, V.Vasic; Vector-controlled multi-phase multi-motor drive systems with a single inverter supply, *Electronics*, vol. 7, no. 2, 2003, pp. 9-20.

***Refereed full conference papers (multiphase drives area only):***

24. S.N.Vukosavic, M.Jones, E.Levi, D.Dujic; Experimental performance evaluation of a five-phase parallel-connected two-motor drive, *IET In. Conf. on Power Electronics, Machines and Drives PEMD,* York, UK, 2008, pp. 686-690.
25. D.Dujic, M.Jones, E.Levi; Space vector PWM for nine-phase VSI with sinusoidal output voltage generation, *IEEE Ind. Elec. Soc. Annual Meeting IECON,* Taipei, Taiwan, 2007, pp. 1524-1529.
26. M.J.Duran, S.Toral, F.Barrero, E.Levi; Real-time implementation of multi-dimensional five-phase space vector PWM using look-up table techniques, *IEEE Ind. Elec. Soc. Annual Meeting IECON,* Taipei, Taiwan, 2007, pp. 1518-1523.
27. D.Dujic, M.Jones, E.Levi; Continuous carrier-based vs. space vector PWM for five-phase VSI, *The IEEE Region 8 EUROCON 2007: Int. Conf. on 'Computer as a Tool'*, Warsaw, Poland, 2007, pp. 1772-1779.
28. M.J.Duran, F.Barrero, S.Toral, E.Levi; Multi-dimensional space vector pulse width modulation for disturbance-free operation of a five-phase AC motor drive, *12$^{th}$ European*

*Conf. on Power Electronics and Applications EPE,* Aalborg, Denmark, 2007, CD-ROM Paper No. 796.

29. D.Dujic, E.Levi, M.Jones, G.Grandi, G.Serra, A.Tani; Continuous PWM techniques for sinusoidal voltage generation with seven-phase voltage source inverters, *IEEE Power Electronics Spec. Conf. PESC,* Orlando, FL, 2007, pp. 47-52.
30. M.J.Duran, S.Toral, F.Barrero, E.Levi; Multi-dimensional space vector pulse width modulation scheme for five-phase series-connected two-motor drives, *IEEE Int. Electric Machines and Drives Conf. IEMDC,* Antalya, Turkey, 2007, pp. 1208-1214.
31. M.J.Duran, E.Levi; Multi-dimensional approach to multi-phase space vector pulse width modulation, *IEEE Ind. Elec. Soc. Annual Meeting IECON,* Paris, France, 2006, pp. 2103-2108.
32. M.Jones, E.Levi, S.N.Vukosavic; Independent control of two five-phase induction machines connected in parallel to a single inverter supply, *IEEE Ind. Elec. Soc. Annual Meeting IECON,* Paris, France, 2006, 1257-1262.
33. A.Iqbal, E.Levi, M.Jones, S.N.Vukosavic; A PWM scheme for a five-phase VSI supplying a five-phase two-motor drive, *IEEE Ind. Elec. Soc. Annual Meeting IECON,* Paris, France, 2006, pp. 2575-2580.
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35. M.Jones, E.Levi, S.N.Vukosavic; A parallel-connected vector-controlled five-phase two-motor drive, *Int. Conf. on Electrical Machines ICEM,* Chania, Greece, 2006, CD-ROM Paper No. PMA2-19.
36. E.Levi, M.Jones, S.N.Vukosavic, H.A.Toliyat; Stator winding design for multi-phase two-motor drives with single VSI supply, *Int. Conf. on Electrical Machines ICEM,* Chania, Greece, 2006, CD-ROM Paper No. OMM2-1.
37. A.Iqbal, E.Levi; Space vector PWM for a five-phase VSI supplying two five-phase series-connected machines, *Int. Power Electronics and Motion Control Conf. EPE-PEMC,* Portoroz, Slovenia, 2006, pp. 222-227.
38. A.Iqbal, E.Levi, M.Jones, S.N.Vukosavic; Generalised, sinusoidal PWM with harmonic injection for multi-phase VSIs, *IEEE Power Electronics Spec. Conf. PESC,* Jeju, Korea, 2006, pp. 2871-2877.
39. S.N.Vukosavic, M.Jones, A.Iqbal, E.Levi; Transient performance evaluation of a five-phase series-connected two-motor drive, *IEE Power Electronics, Machines & Drives Conf. PEMD,* Dublin, 2006, pp. 581-585.
40. A.Iqbal, S.Vukosavic, E.Levi, M.Jones, H.A.Toliyat; Dynamics of a series-connected two-motor five-phase drive system with a single-inverter supply, *IEEE Industry Applications Society Annual Meeting IAS,* Hong Kong, 2005, pp. 1081-1088.
41. A.Iqbal, E.Levi; Space vector modulation schemes for a five-phase voltage source inverter, *11th European Conf. on Power Electronics and Applications EPE,* Dresden, Germany, 2005, CD-ROM Paper No. 006.
42. M.Jones, S.N.Vukosavic, E.Levi; Experimental performance evaluation of six-phase series-connected two-motor drive systems, *11th European Conf. on Power Electronics and Applications EPE,* Dresden, Germany, 2005, CD-ROM Paper No. 026.
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45. M.J.Duran, E.Levi, M.Jones; Independent vector control of asymmetrical nine-phase machines by means of series connection, *IEEE Int. Electric Machines and Drives Conf. IEMDC,* San Antonio, TX, 2005, pp. 167-173.
46. M.Jones, E.Levi; Series connected quasi-six-phase two-motor drives with independent control, *Electrimacs,* Hammamet, Tunisia, 2005, CD-ROM Paper No. 100M-Jones.pdf.
47. M.Jones, S.N.Vukosavic, E.Levi, A.Iqbal; A novel six-phase series-connected two-motor drive with decoupled dynamic control, *IEEE Industry Applications Society Annual Meeting IAS,* Seattle, WA, 2004, pp. 639-646.

48. M.Jones, E.Levi; Combining induction and synchronous machines in a seven-phase series-connected three-motor drive, *Int. Power Electronics and Motion Control Conf. EPE-PEMC,* Riga, Latvia, 2004, CD-ROM Paper No. A71123.
49. A.Iqbal, E.Levi; Modelling of a six-phase series-connected two-motor drive system, *Int. Conf. on Electrical Machines ICEM,* Krakow, Poland, 2004, CD-ROM Paper No. 98.
50. M.Jones, E.Levi, A.Iqbal; A five-phase series-connected two-motor drive with current control in the rotating reference frame, *IEEE Power Elec. Spec. Conf. PESC,* Aachen, Germany, 2004, pp. 3278-3284.
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53. E.Levi, A.Iqbal, S.N.Vukosavic, H.A.Toliyat; Modelling and control of a five-phase series-connected two-motor drive, *IEEE Ind. Elec. Soc. Annual Meeting IECON*, Roanoke, Virginia, 2003, pp. 208-213.
54. M.Jones, E.Levi, S.N.Vukosavic, H.A.Toliyat; A novel nine-phase four-motor drive system with completely decoupled dynamic control, *IEEE Ind. Elec. Soc. Annual Meeting IECON*, Roanoke, Virginia, 2003, pp. 637-642.
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56. M.Jones, E.Levi, S.N.Vukosavic, H.A.Toliyat; Independent vector control of a seven-phase three-motor drive system supplied from a single voltage source inverter, *IEEE Power Elec. Spec. Conf. PESC,* Acapulco, Mexico, 2003, pp. 1865-1870.
57. M.Jones, E.Levi; A literature survey of state-of-the-art in multiphase AC drives, *37th Int. Universities Power Engineering Conference UPEC*, Stafford, UK, 2002, CD-ROM Paper No. 46, pp. 505-510.

***Other relevant data:***

Associate Editor, IEEE Trans. on Industrial Electronics
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