Universidad del Cono Sur de las Américas Centro Tecnológico

ACE-TI

Multiphase Generators and Drives

Federico Barrero - University of Seville, SPAIN

ENERPY 2019

Summary

1. Something about me …
2. Multiphase machines
   1. Applications
   2. Control
3. Conclusions

Something about me …

PhD degree in Electrical and Electronic Engineering from the University of Seville, Spain, in 1998.

Full Professor at the University of Seville since Nov 2016.

Interesting research fields:
Control of electrical drives: multiphase ones in recent times
Embedded systems in ITS

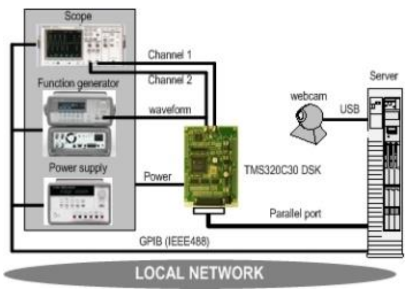
CV full details:

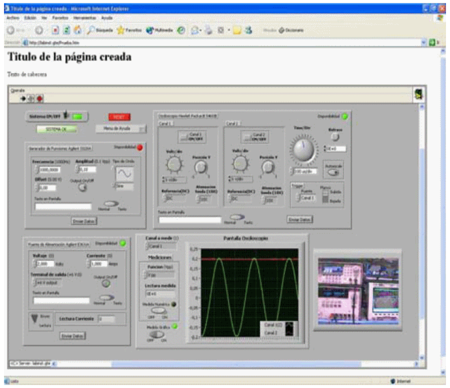
University of Seville: http://investigacion.us.es/sisius/sis_showpub.php?idpers=3201
Researcher ID: A-9626-2013
Google Scholar: http://scholar.google.com/citations?user=B4ouwAgAAAAJ&hl=es
Research Gate: https://www.researchgate.net/profile/Federico_Barrero

Something about me …

TEACHING EXPERIENCE

- 24 years of teaching experience to undergraduate students at an Engineering School (University of Seville)
- 17 years of teaching experience to graduate students at an Engineering School (University of Seville)
- Teaching in 17 different courses in 5 Engineering Degrees (Electronic Engineering field at the University of Seville). Principal lecturer in 6 of these courses
- Teaching in 4 different courses in MSc Engineering Degrees (Electronic Engineering field at the University of Seville). Principal lecturer in 2 of these courses
- Supervisor of 12 completed PhD students
- Supervisor of 12 MSc and 70 BSc final projects
- Principal lecturer in 9 innovative teaching projects. About 40 k EUR granted
- 5 edited books in the embedded systems' field:





Remote labs for managing microprocessors (DSPs)

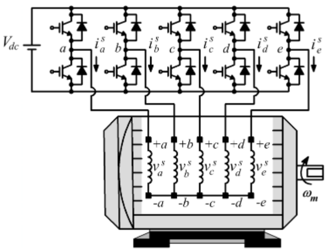
McGRAW HILL

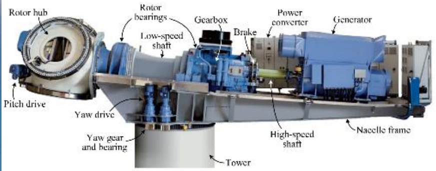
Something about me …

RESEARCH EXPERIENCE

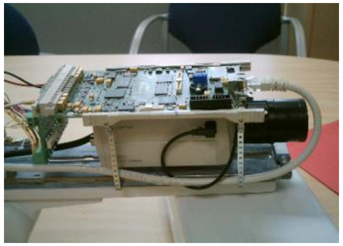
Research fields

Control of multiphase drives





Embedded systems and smart sensors



Embedded multimedia processors,

ITS Systems and Applications

Research responsibilities

- More than 1.6 million EUR granted in total (public funds)
- More than 250000 EUR granted in total (private funds)
- Supervision of PhD Students: 12 completed students (2 in process)
- Researcher of ACETI research group

ACE-TI

Something about me …

RESEARCH EXPERIENCE

Research production

- ISI journals: more than 100
- About 180 conference papers

Awards and Recognitions

- Full Professor credentials from the Spanish Government since March, 2012
- Full Professor since 2016
- Senior member IEEE in 2005
- Best IEEE TIE paper award for the paper published in 2009
- Best IET EPA paper award for the paper published in 2010-2011
- Best conference paper award: 6

Something about me …

Madrid

Barcelona

Sevilla

https://www.youtube.com/watch?v=LnV7IkZU-OY

Real Betis: https://www.youtube.com/watch?v=TFVfkZXQrEY

Something about me …

http://www.us.es

Established in	1505
Alumni	85000
Undergrad. Degrees	67
Máster Degree	92
PhD Degree	99

http://www.esi.us.es

Campus de Excelencia Internacional with UMA

Alumni	6000

Multiphase machines

E. Levi, “Multiphase electric machines for variable-speed applications,” *IEEE Trans. on Ind. Electron.*, vol. 55, no. 5, pp. 1893-1909, 2008.

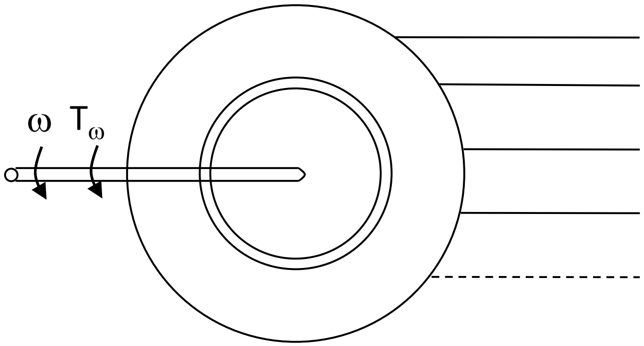
E. Levi, “Advances in converter control and innovative exploitation of additional degrees of freedom for multiphase machines,” *IEEE Trans. on Ind. Electron.*, vol. 63, 2016.

F. Barrero and M.J. Duran, “Recent advances in the design, modeling and control of multiphase machines – Part 1,” *IEEE Trans. on Ind. Electron.*, vol. 63, 2016.

M.J. Duran and F. Barrero, “Recent advances in the design, modeling and control of multiphase machines – Part 2,” *IEEE Trans. on Ind. Electron.*, vol. 63, 2016.

SS on “Multiphase Machines and Drives – Revisited” vol. 63 at TIE in 2016.

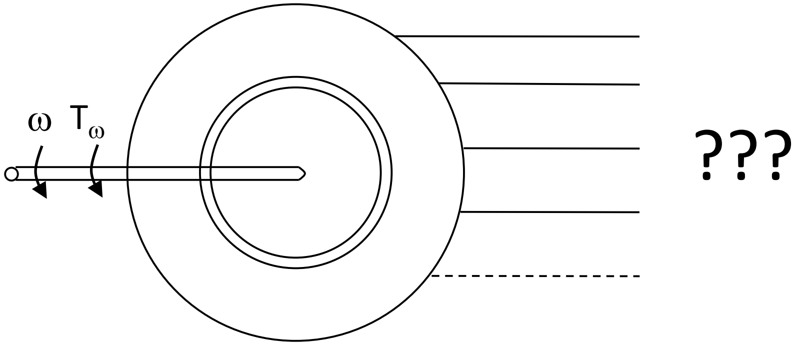
Multiphase machines



???

What does multiphase mean?

Multiphase machines



Why multiphase?

- First of all … **Why not**?
- Machine supplied from converter ⇒
  Any number of phases is feasible

Multiphase machines

Many advantages …

- The power is splitted (lower stator losses)
- The fault-tolerant operation is allowed
- There is harmonic cancellation (ripple, vibration, noise)
- Torque enhancement is allowed (concentrated windings)
- More stability can be obtained
- Multi-motor drives can be used

Multiphase machines

Other considerations …

- The concept is not new, the origin of a six-phase generator can be traced back to 1929-1930: a machine with two in-phase three-phase winding was actually utilized in the States.

- Now both signal processing and power electronics are adequate for its use and the topic has re-emerged.

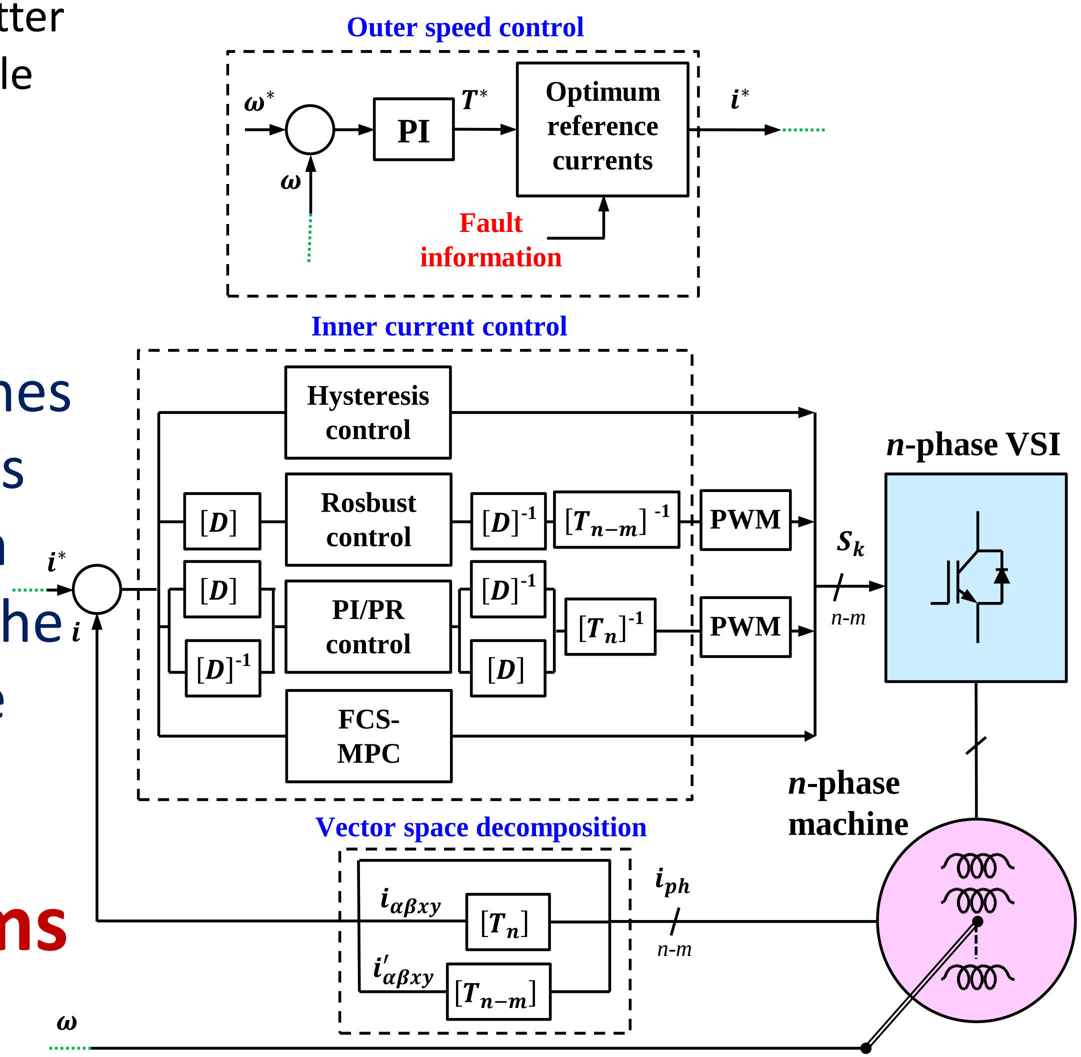
- Emerging applications are suitable for the use of multiphase drives.

Multiphase machines

Intrinsic features: power splitting, better fault tolerance or lower torque ripple than three-phase machines

Attractive alternative to conventional three-phase ones in a number of applications where high overall system reliability and reduction in the total power per phase are required

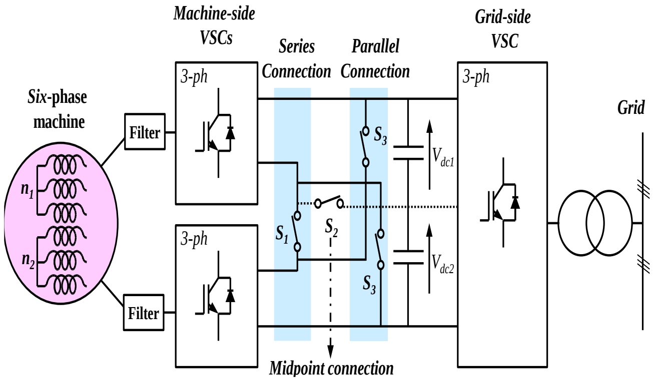
Many, many problems to solve …



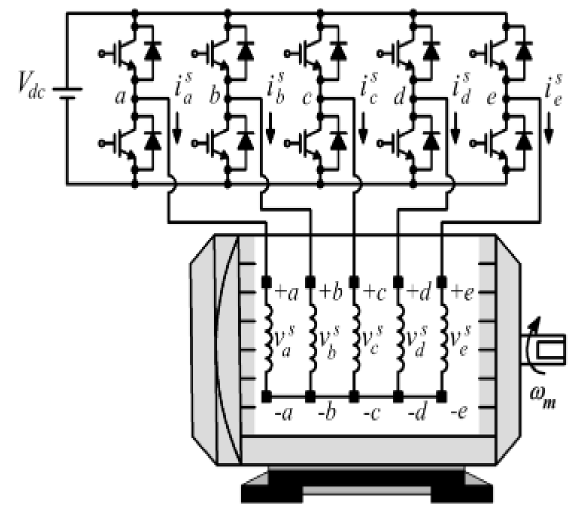
Multiphase machines

- The model differs according to the type of winding (concentrated or distributes), the number of phases (odd or even), isolated/non-isolated neutrals
- The machine can be modeled in different ways
  - Phase-variable model
  - Vector decomposition approach (VSD)
  - Double-dq approach
- The model depends of course on the type of machines
  - PM synchronous machines
  - Induction Machines

Main Problem (Complexity)



$n = 3 \cdot k$



Multiphase machines

- Phase variable model for distributed-winding machines

$$\underline{v}^s = \underline{R}_s \underline{i}^s + \frac{d\underline{\psi}^s}{dt} \qquad \underline{\psi}^s = \underline{L}_s \underline{i}^s + \underline{L}_{sr} \underline{i}^r$$

$$\underline{v}^r = \underline{R}_r \underline{i}^r + \frac{d\underline{\psi}^r}{dt} \qquad \underline{\psi}^r = \underline{L}_r \underline{i}^r + \underline{L}_{rs}$$

$$\underline{L}_s = \begin{bmatrix} L_{11s} & L_{12s} & L_{13s} & \ldots\ldots & L_{1ns} \\ L_{21s} & L_{22s} & L_{23s} & \ldots\ldots & L_{2ns} \\ L_{31s} & L_{32s} & L_{33s} & \ldots\ldots & L_{3ns} \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots \\ L_{n1s} & L_{n2s} & L_{n3s} & \ldots\ldots & L_{nns} \end{bmatrix} = \begin{bmatrix} L_{ls}+M & M\cos\alpha & M\cos 2\alpha & \ldots\ldots & M\cos(n-1)\alpha \\ M\cos(n-1)\alpha & L_{ls}+M & M\cos\alpha & \ldots\ldots & M\cos(n-2)\alpha \\ M\cos(n-2)\alpha & M\cos(n-1)\alpha & L_{ls}+M & \ldots\ldots & M\cos(n-3)\alpha \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots \\ M\cos\alpha & M\cos 2\alpha & M\cos 3\alpha & \ldots\ldots & L_{ls}+M \end{bmatrix}$$

$$\underline{L}_r = \begin{bmatrix} L_{11r} & L_{12r} & L_{13r} & \ldots\ldots & L_{1nr} \\ L_{21r} & L_{22r} & L_{23r} & \ldots\ldots & L_{2nr} \\ L_{31r} & L_{32r} & L_{33r} & \ldots\ldots & L_{3nr} \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots \\ L_{n1r} & L_{n2r} & L_{n3r} & \ldots\ldots & L_{nnr} \end{bmatrix} = \begin{bmatrix} L_{lr}+M & M\cos\alpha & M\cos 2\alpha & \ldots\ldots & M\cos(n-1)\alpha \\ M\cos(n-1)\alpha & L_{lr}+M & M\cos\alpha & \ldots\ldots & M\cos(n-2)\alpha \\ M\cos(n-2)\alpha & M\cos(n-1)\alpha & L_{lr}+M & \ldots\ldots & M\cos(n-3)\alpha \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots \\ M\cos\alpha & M\cos 2\alpha & M\cos 3\alpha & \ldots\ldots & L_{lr}+M \end{bmatrix}$$

The model can be further simplified providing a better insight into the physical phenomena involved in the machine

Multiphase machines

Vector decomposition approach (VSD)

It is a generalization of the Clarke/Park Transformation (power invariant) introduced by Zhao & Lipo to SIMPLIFY

$$
\mathbf{C} = \sqrt{\frac{2}{n}}
\begin{array}{c}
\alpha \\ \beta \\ x_1 \\ y_1 \\ x_2 \\ y_2 \\ \cdots \\ x_{\frac{n-4}{2}} \\ y_{\frac{n-4}{2}} \\ 0_+ \\ 0_-
\end{array}
\left[\begin{array}{cccccccc}
1 & \cos\alpha & \cos 2\alpha & \cos 3\alpha & \ldots\ldots & \cos 3\alpha & \cos 2\alpha & \cos\alpha \\
0 & \sin\alpha & \sin 2\alpha & \sin 3\alpha & \ldots\ldots & -\sin 3\alpha & -\sin 2\alpha & -\sin\alpha \\
1 & \cos 2\alpha & \cos 4\alpha & \cos 6\alpha & \ldots\ldots & \cos 6\alpha & \cos 4\alpha & \cos 2\alpha \\
0 & \sin 2\alpha & \sin 4\alpha & \sin 6\alpha & \ldots\ldots & -\sin 6\alpha & -\sin 4\alpha & -\sin 2\alpha \\
1 & \cos 3\alpha & \cos 6\alpha & \cos 9\alpha & \ldots\ldots & \cos 9\alpha & \cos 6\alpha & \cos 3\alpha \\
0 & \sin 3\alpha & \sin 6\alpha & \sin 9\alpha & \ldots\ldots & -\sin 9\alpha & -\sin 6\alpha & -\sin 3\alpha \\
\ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots \\
1 & \cos\left(\frac{n-2}{2}\right)\alpha & \cos 2\left(\frac{n-2}{2}\right)\alpha & \cos 3\left(\frac{n-2}{2}\right)\alpha & \ldots\ldots & \cos 3\left(\frac{n-2}{2}\right)\alpha & \cos 2\left(\frac{n-2}{2}\right)\alpha & \cos\left(\frac{n-2}{2}\right)\alpha \\
0 & \sin\left(\frac{n-2}{2}\right)\alpha & \sin 2\left(\frac{n-2}{2}\right)\alpha & \sin 3\left(\frac{n-2}{2}\right)\alpha & \ldots\ldots & -\sin 3\left(\frac{n-2}{2}\right)\alpha & -\sin 2\left(\frac{n-2}{2}\right)\alpha & -\sin\left(\frac{n-2}{2}\right)\alpha \\
1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & \ldots\ldots & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\
1/\sqrt{2} & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} & \ldots\ldots & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2}
\end{array}\right]
$$

The matrix is different if the number of phases is odd or even and if the neutrals are connected or isolated

Multiphase machines

The rotational transformation remains as in three-phase machines and just applies to α-β components, which are usually termed *d*-*q* when expressed in rotated frame.

$$\underline{D}_s = \begin{bmatrix} \cos\theta_s & \sin\theta_s & & & \\ -\sin\theta_s & \cos\theta_s & & & \\ & & 1 & & \\ & & & ..... & \\ & & & & 1 \end{bmatrix} \qquad \underline{D}_s^{-1} = \begin{bmatrix} \cos\theta_s & -\sin\theta_s & & & \\ \sin\theta_s & \cos\theta_s & & & \\ & & 1 & & \\ & & & ..... & \\ & & & & 1 \end{bmatrix}$$

$$\underline{D}_r = \begin{bmatrix} \cos\beta & \sin\beta & & & \\ -\sin\beta & \cos\beta & & & \\ & & 1 & & \\ & & & ..... & \\ & & & & 1 \end{bmatrix} \qquad \underline{D}_r^{-1} = \begin{bmatrix} \cos\beta & -\sin\beta & & & \\ \sin\beta & \cos\beta & & & \\ & & 1 & & \\ & & & ..... & \\ & & & & 1 \end{bmatrix}$$

Multiphase machines

Meaning of the components

- The first stator–rotor pair (α–β subspace) represents the fundamental supply component plus supply harmonic (of the order 12n±1 (n=1,2,3,…) in 6ph-machines).
- The other stator–rotor pairs (x–y subspace)represent supply harmonic (of the order 6n±1 with n=1,3,5,…).
- The rest of the components are the zero sequence harmonic components which disappear if isolated neutral points are assumed.
- NOTE: an important feature of the transformation is that all subspaces are orthogonal.

Differences in distributed and concentrated-winding machines

- In distributed-winding machines the x-y components are not involved in the electromechanical energy conversion process, the flux is mutually cancelled and the rotor is not linked. These components just generate stator Joule losses. NOT DESIRED.
- In concentrated-winding machines the x-y components (also termed d_3-q_3 in five-phase machines) interact with the higher order spatial harmonics of the airgap and produce an additional torque. This leads to torque enhancement and higher power density. CAN DE OF INTEREST.

$$T_e = T_{e1} + T_{e3} = P(L_{m1} / L_{r1})(\psi_{dr1} i_{qs1} - \psi_{qr1} i_{ds1}) + 3P(L_{m3} / L_{r3})(\psi_{dr3} i_{qs3} - \psi_{qr3} i_{ds3})$$

Multiphase machines

APPLICATIONS

Multiphase machines

PROPOSED APPLICATIONS TIED TO TYPE OF MULTIPHASE MACHINE

Type of machine	Ref.	Application
Induction Machine	[8]	Submersible 5-phase pump motor
FSCW PM (SPM type)	[9,10] [17]	Fault-tolerant 6- and 5-phase in-wheel motor for electric vehicle 6-phase generator inside the aircraft main gas turbine engine
FSCW PM (IPM type)	[20]	2.1 MW 5-phase marine propeller
BPM	[25]	4- and 5-phase electromechanical flight control surface actuator
REL	[27]	5-phase axial-flux configuration for electric vehicles
BLDC	[30]	12 kW 5-phase electro hydrostatic actuator for aerospace application
Superconducting Machines	[34,35]	Design of 12 MW 9- and dual-3-phase synchronous generators

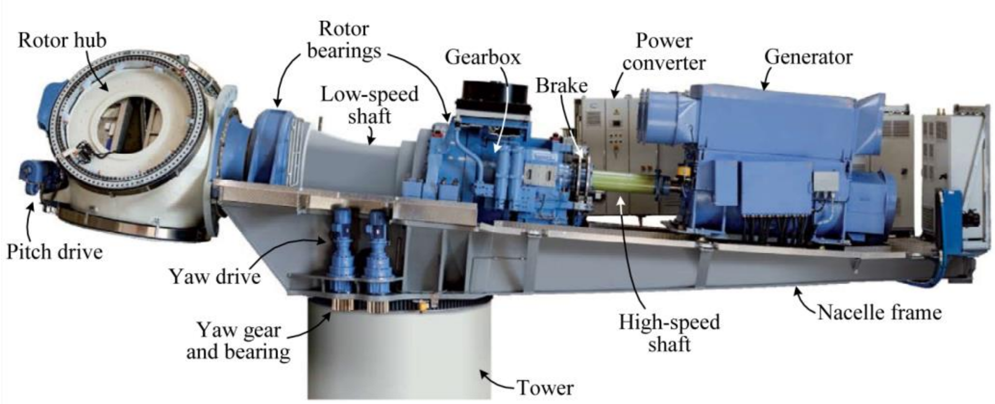
Multiphase machines

MULTIPHASE GENERATION SYSTEMS (MACHINE AND POWER CONVERTER TYPE) IN PROPOSED APPLICATIONS

Machine type	Converter type	Ref.	Applications
PMSM (SPM type)	3x BTB VSCs	[42]	9-phase 1.1 MW generator in regenerative braking
PMSG	4x BTB VSCs	[44]	12-phase 5 MW WECS
Flux switching PMSG	12x BTB VSCs	[45]	36-phase 500 kW WECS
Axial flux PMSG	9x series VSCs	[47]	27-phase multi-MW WECS
PMSG (SPM type)	4x series/parallel Vienna rectifier	[49]	12-phase multi-MW WECS
SCIG	2x DR + 1x VSC	[55]	9-phase stand-alone WECS
WRSM/PMSM	3x DR/DR+DC/DC	[61] [62]	9-phase 2 MW shipboard DC generation system

Multiphase machines

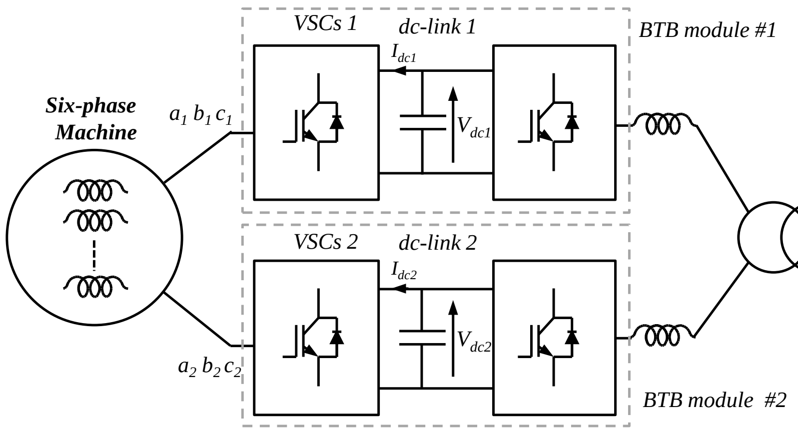
Electric generators in renewable energy



Most of these developments have been done using conventional three-phase drives, but multiphase drives possess certain advantages that could make them a key player in the near future

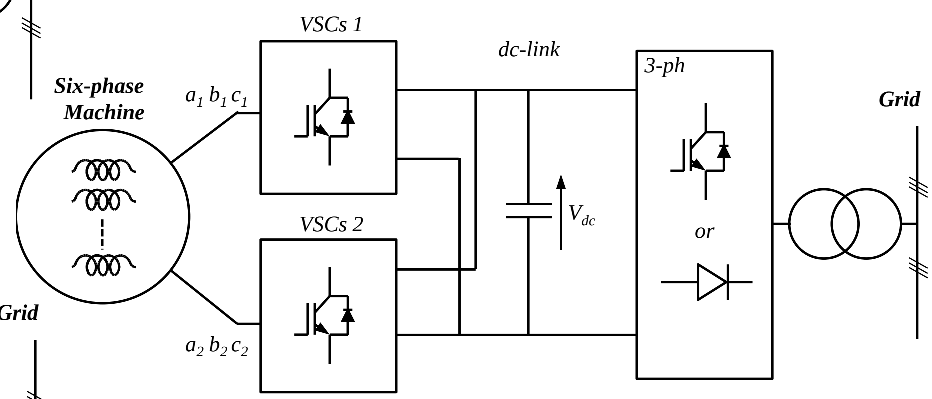
Multiphase machines

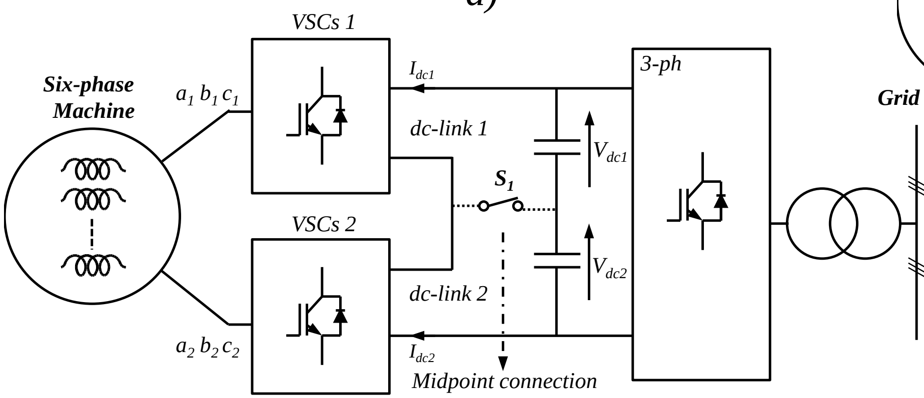
Multiphase generating topologies



a)

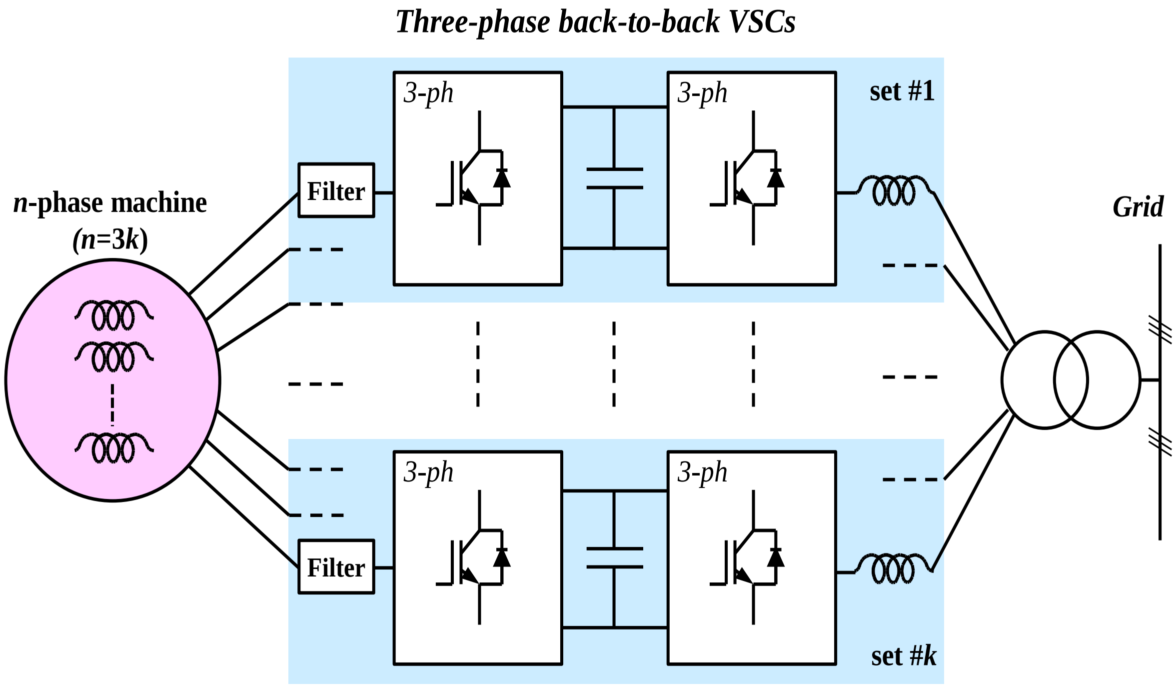
Many different topologies can be explored for multiphase wind energy systems.





Multiphase machines

Examples of industry implementations are the multi-phase generators from GAMESA for 4.5 and 5 MW: 18-phase medium-speed PMSG drive using k=6 sets of three-phase windings and 750 kW IGBT-based BTB converters to reach 4.5 MW at 690 V.



Multiphase machines

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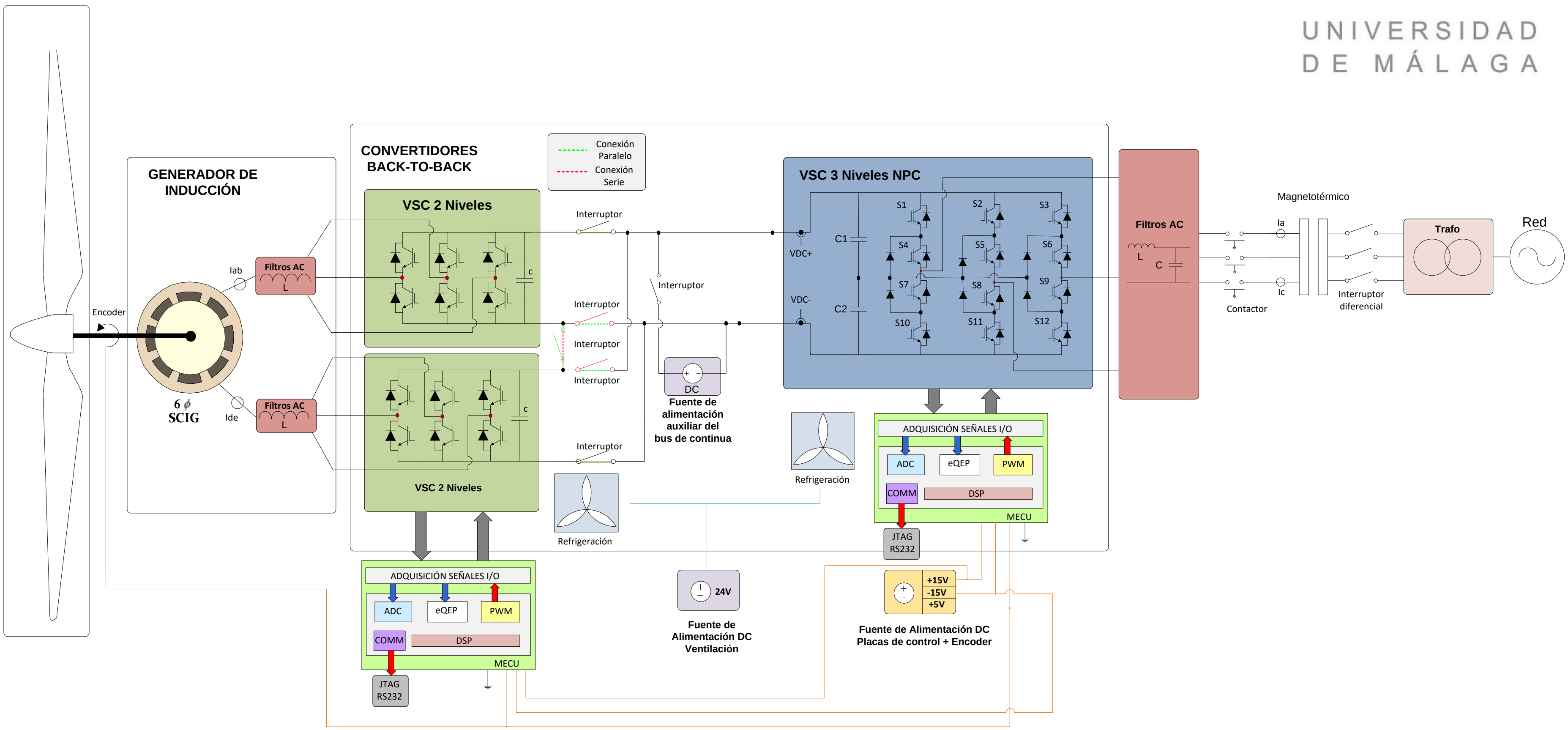
UNIVERSIDAD DE MÁLAGA

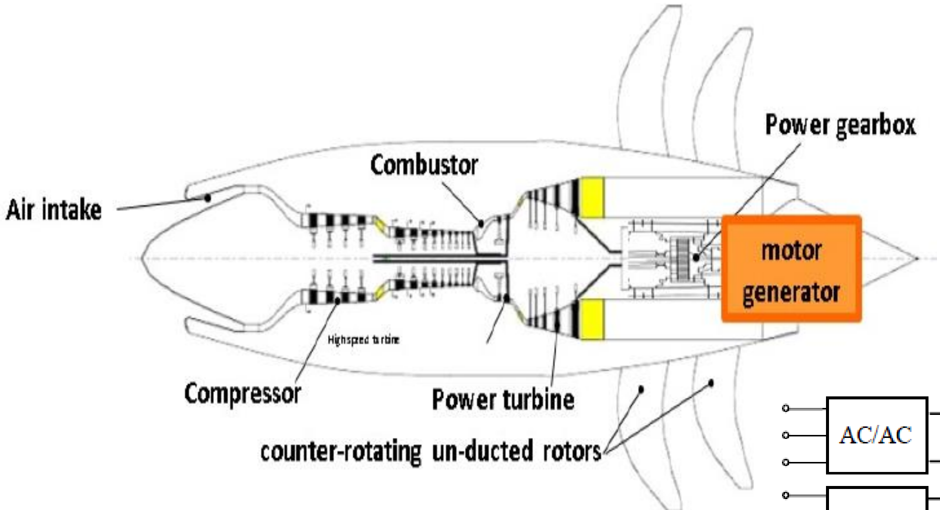


Multiphase machines

MEA: More Electric Aircrafts

Shaft-Line-Embedded Multiphase Starter/Generator for Aero-Engine

R. Bojoi, A. Cavagnino, A. Tenconi and S. Vaschetto (Politecnico di Torino)



SS on "Multiphase Machines and Drives – Revisited" to be published at TIE in 2016

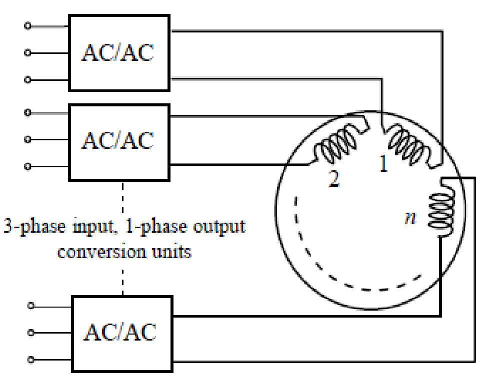


Fig. 2. Fault tolerant drive with multiple single-phase units.

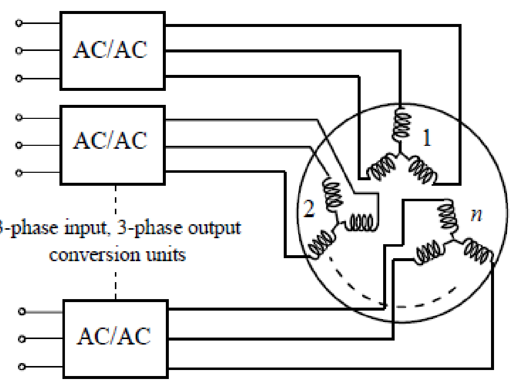
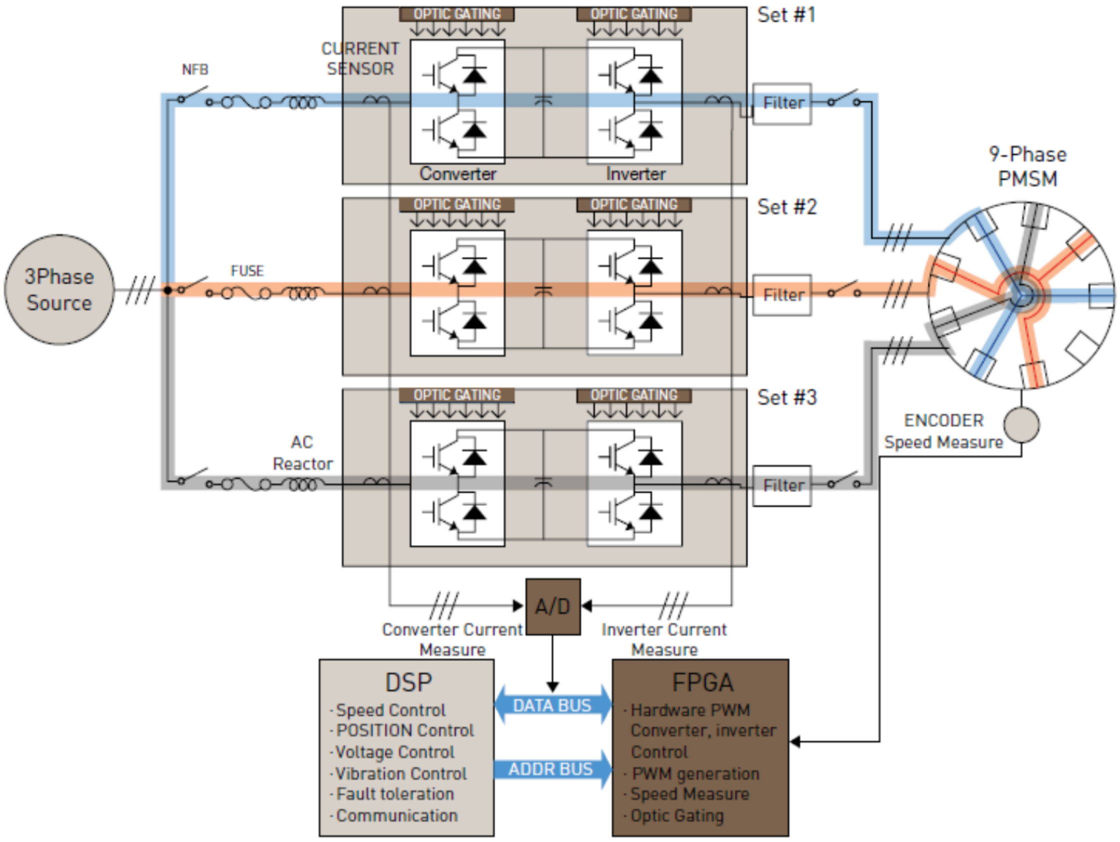
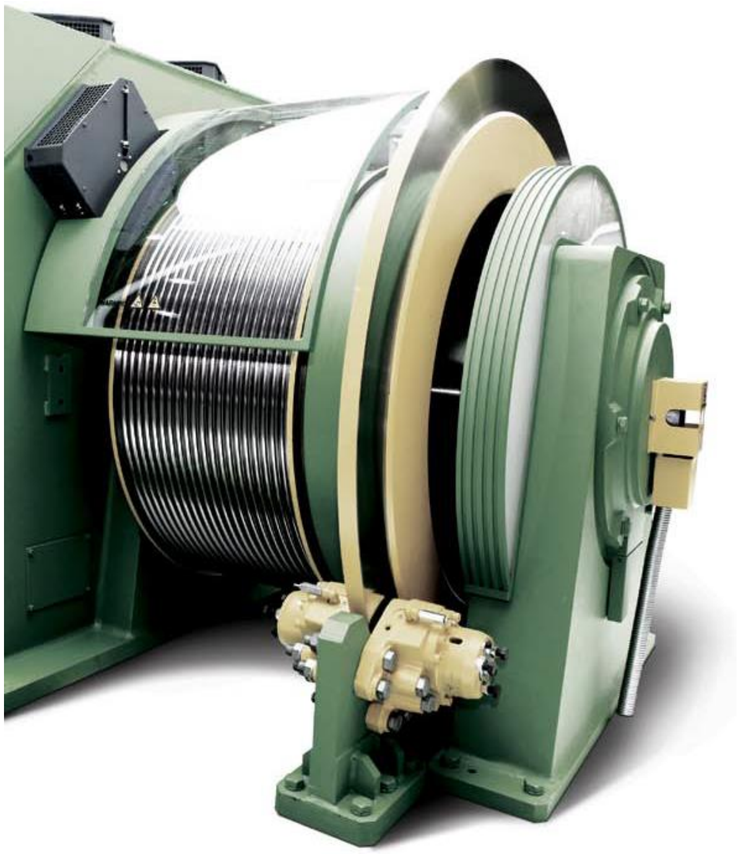


Fig. 3. Fault tolerant drive with multiple 3-phase units.

Multiphase machines

Hyundai High Speed Elevator
9-phase PMSM with three two level B2B converters





Multiphase machines

Submarines:
- 12-Phase PM (SIEMENS)
- 13-Phase PM

Multiphase machines

HMS *Daring* - March 2010

Electric propulsion in war ships: Type 45 destroyer

ALSTOM ('Advanced induction motor')

15-phase, 19 MW

3.7 kV, 0-15 Hz, 12-pole (150 rpm)

5 Isolated neutrals

Multiphase machines

Integration of Multi propulsion power train

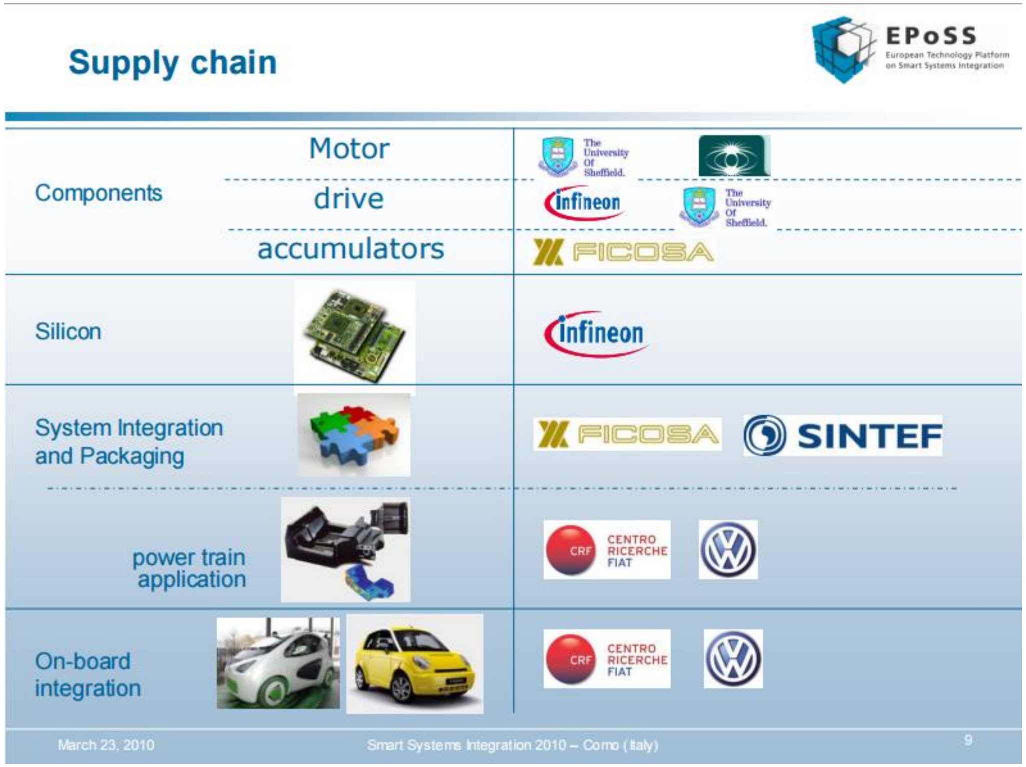
European Green Vehicles Initiative (EGVI) through Grant No. 260176.

Project acronym: CASTOR

Project name: car multi propulsion integrated power train

New winding configurations for 6-phase permanent magnet (18-slot, 8-pole, rated for 41kW peak power for electric vehicles) brushless machines that reduce undesirable space harmonics in the stator MMF are proposed.

A prototype machine drive (motor and inverter) is introduced and its architectural advantages are explored as a fully integrated powertrain for Electric Vehicle propulsion systems.



Multiphase machines

http://www.comarth.com/es/

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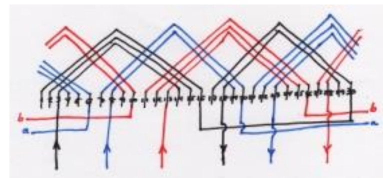
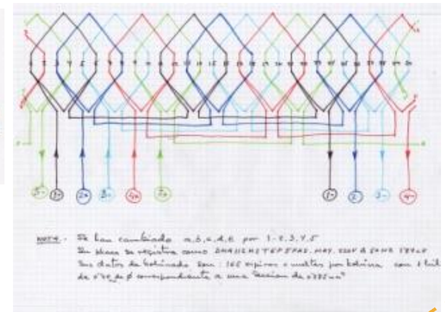
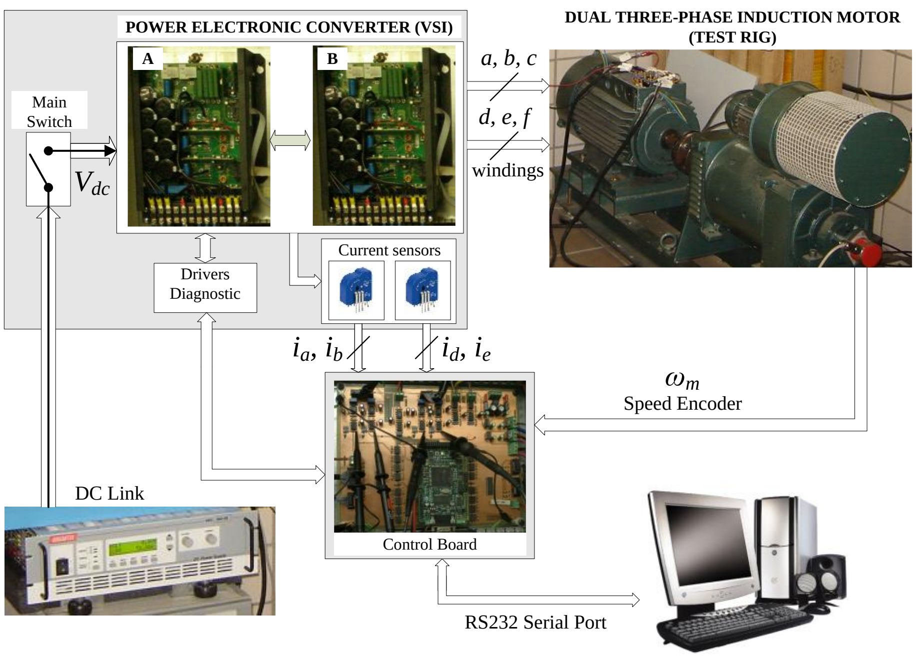
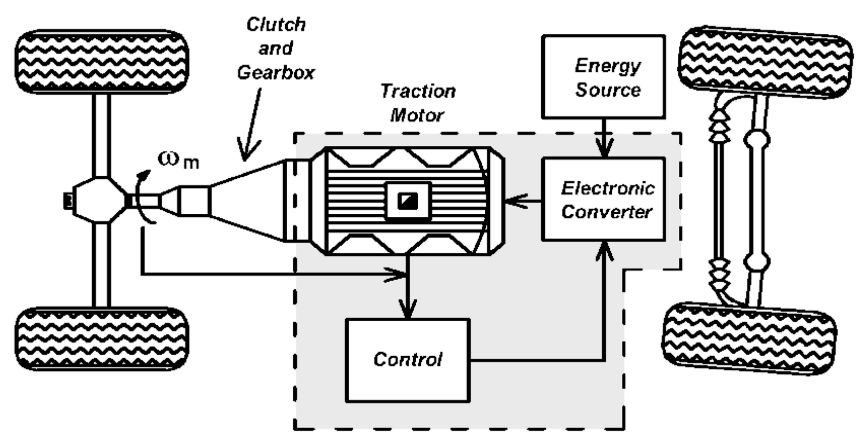
Multiphase machines









Multiphase machines

V2G Applications

LIVERPOOL JOHN MOORES UNIVERSITY

SS on "Multiphase Machines and Drives – Revisited" to be published at TIE in 2016

Reuse the existing inverter and propulsion multiphase machine in EVs during the battery charging process, achieving substantial savings on the space, weight and cost.

Symmetrical and asymmetrical six-phase machines are considered

Isolation is used off-board on the grid side.

The charging/V2G modes of operation are answered without torque production: rotor at standstill; mechanical lock avoided.

Fast charging due to less power limitation than in conventional single-phase chargers

Multiphase machines

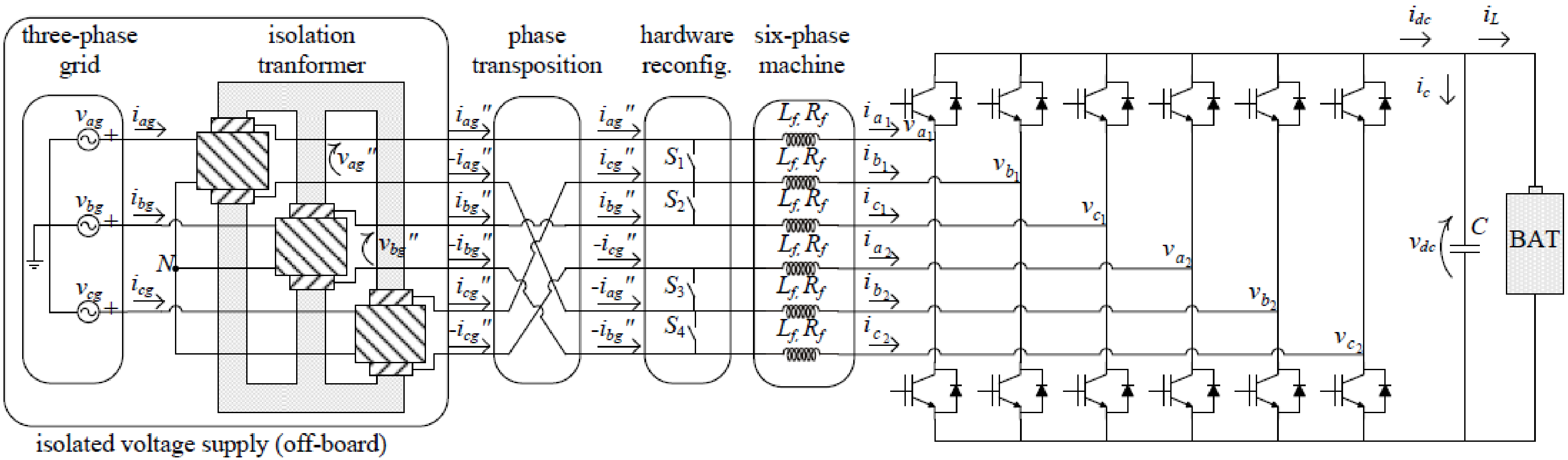


Fig. 1. Topology of the isolated charger incorporating a symmetrical six-phase machine. Grid connection system does not require a transformer with dual secondary (as in [15]) to create a symmetrical six-phase voltage supply for charging/V2G modes.

V2G Applications

Minor drawback

The proposal requires a hardware reconfiguration using four added switches for the charging/vehicle-to-grid modes of operation.

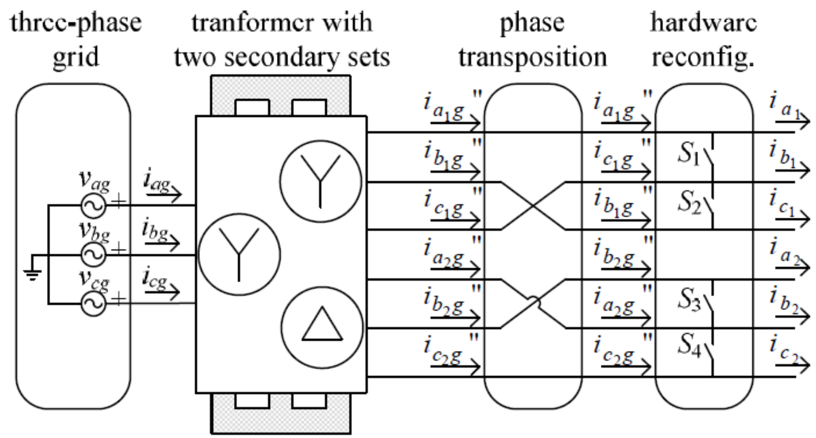
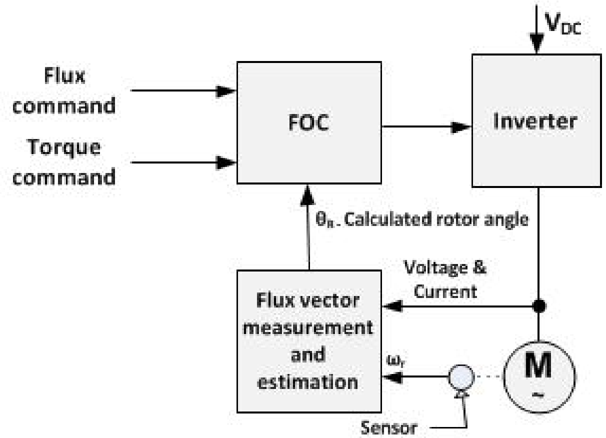


Fig. 2. Connections of isolated charger incorporating an asymmetrical six-phase machine (the right part is the same as in Fig. 1).

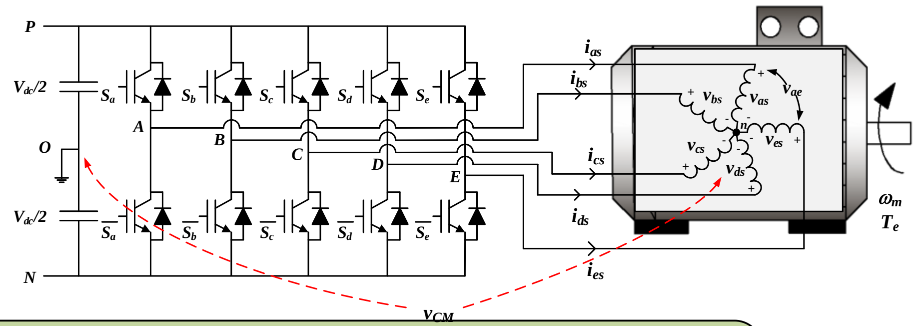
Multiphase machines

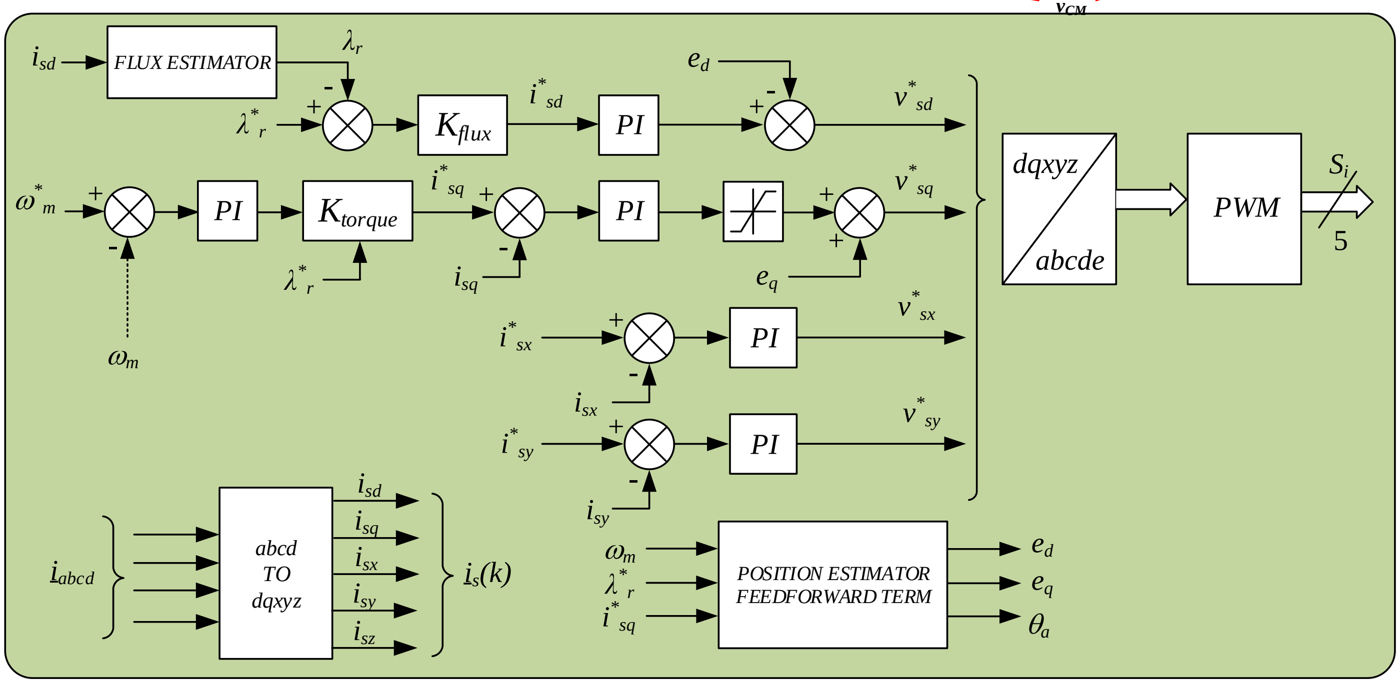
CONTROL

Multiphase machines



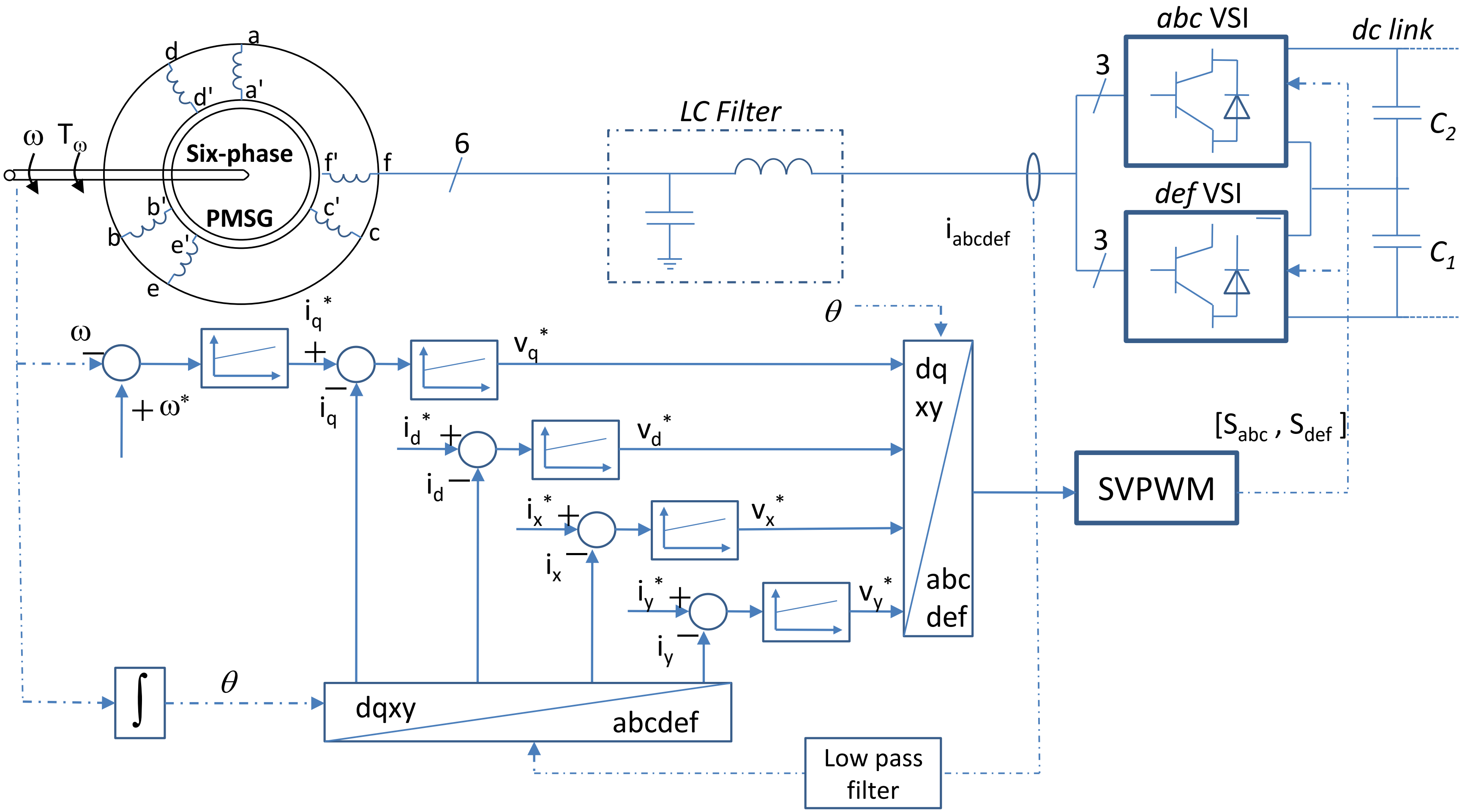
Field Oriented Control (FOC)





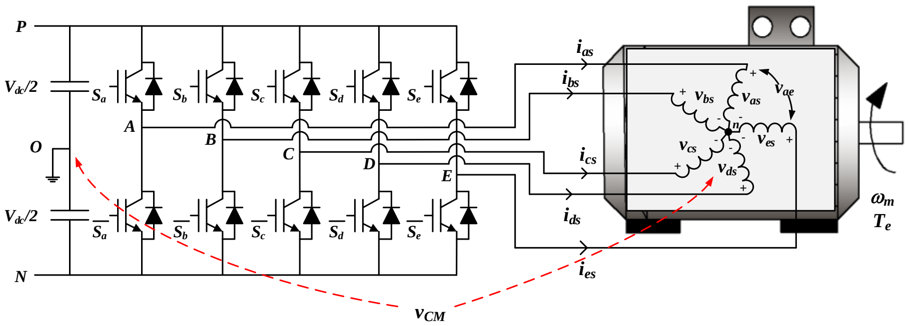
Multiphase machines

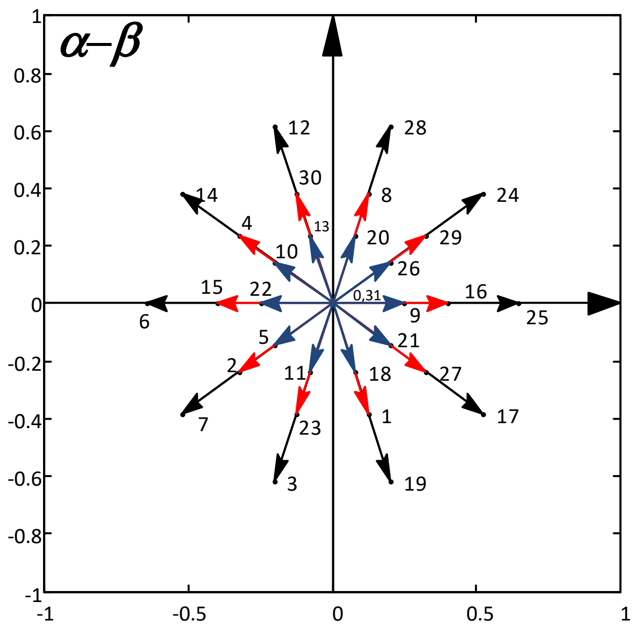
The classical control schemes remain basically the same but new controllers modified modulation techniques are necessary

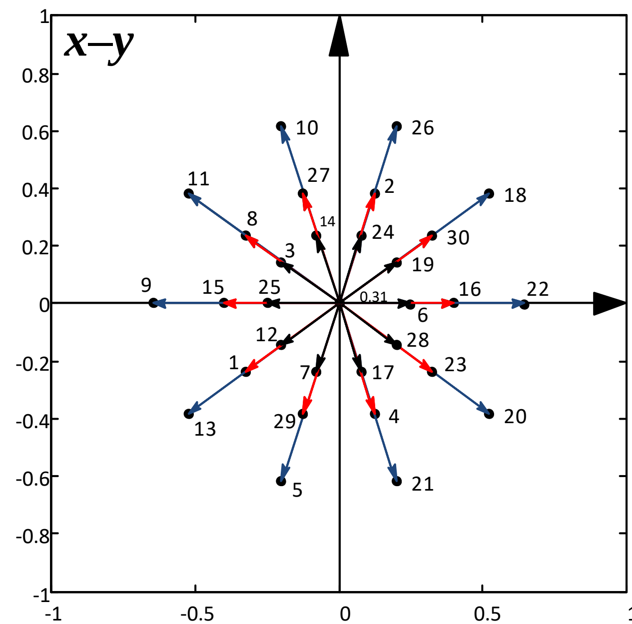


Multiphase machines

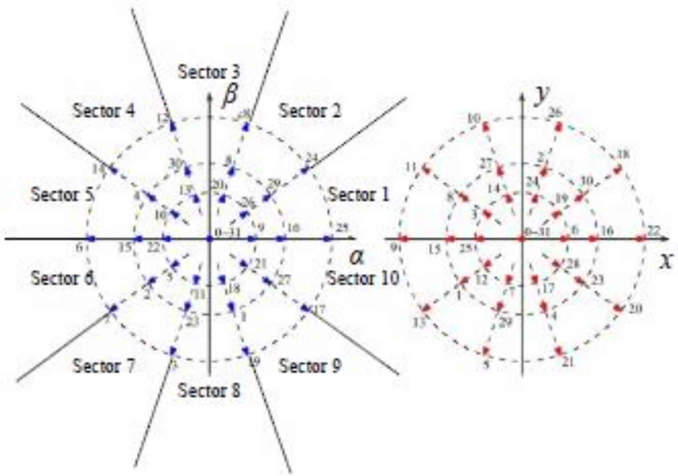
Field Oriented Control (FOC)

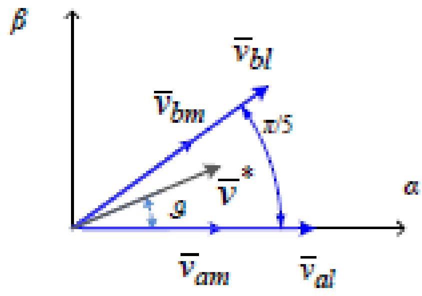


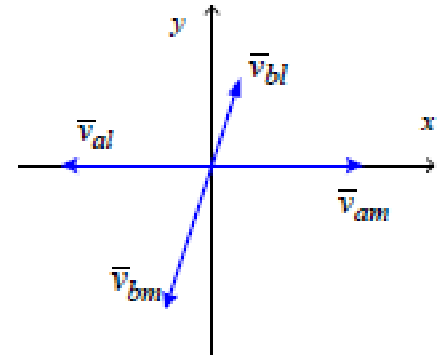




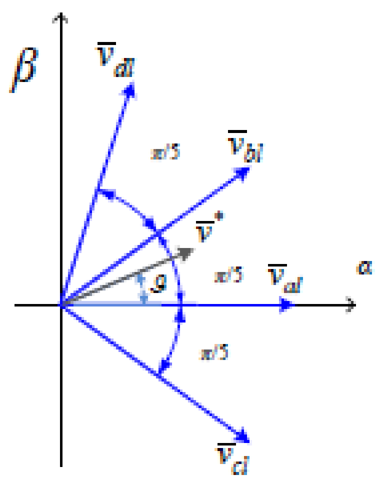
Multiphase machines

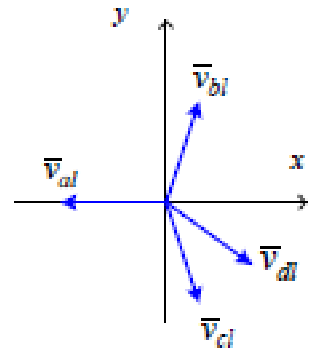






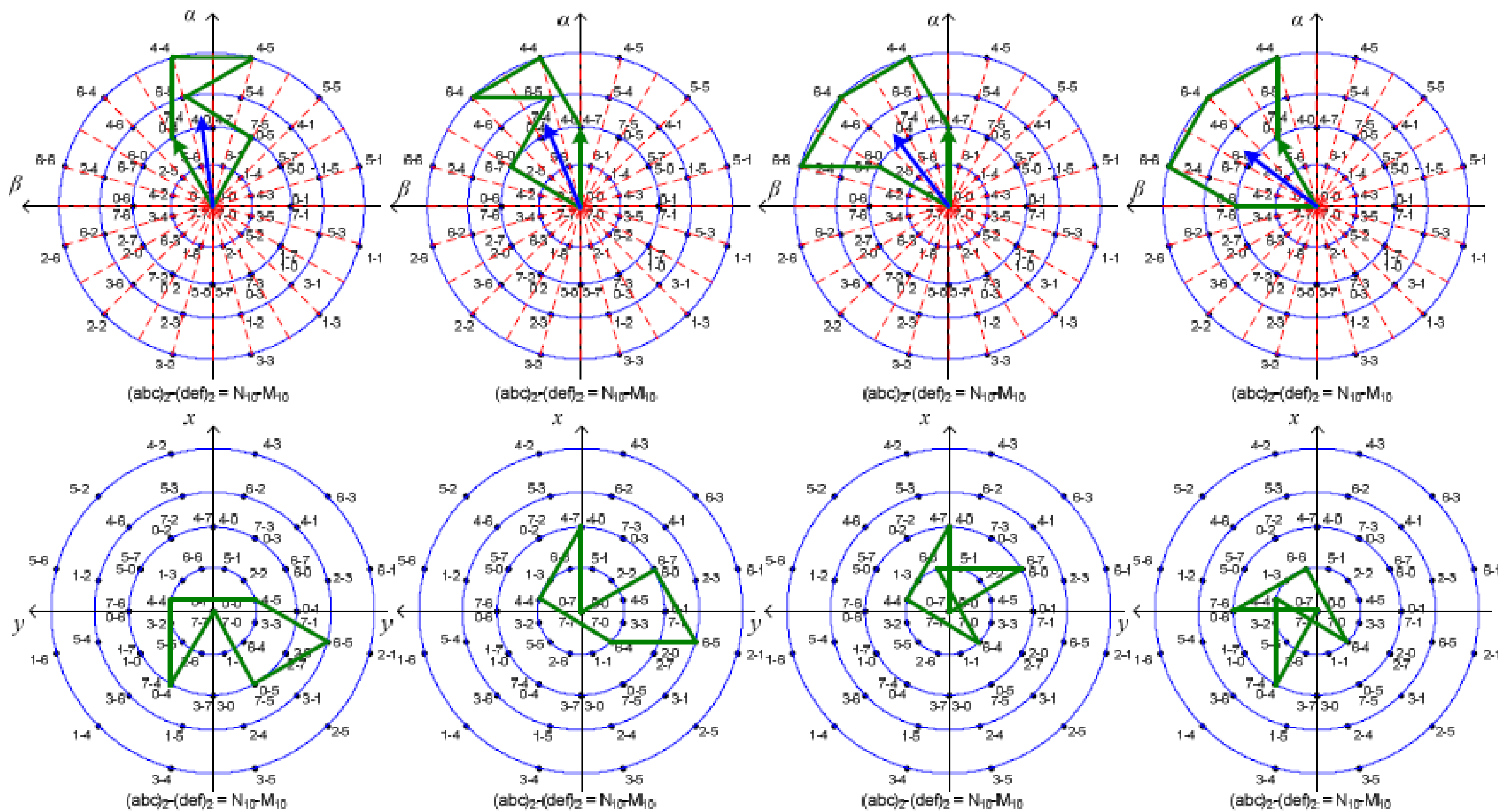
Ways to select the applied voltage vectors





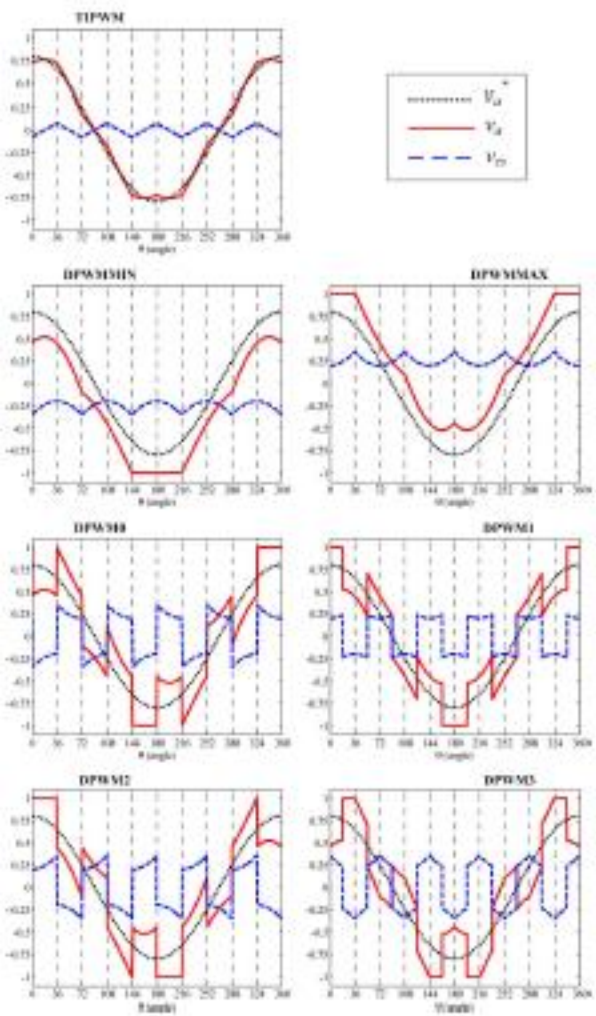
Multiphase machines

Ways to select the applied the sequence of voltage vectors and ZERO voltage vectors



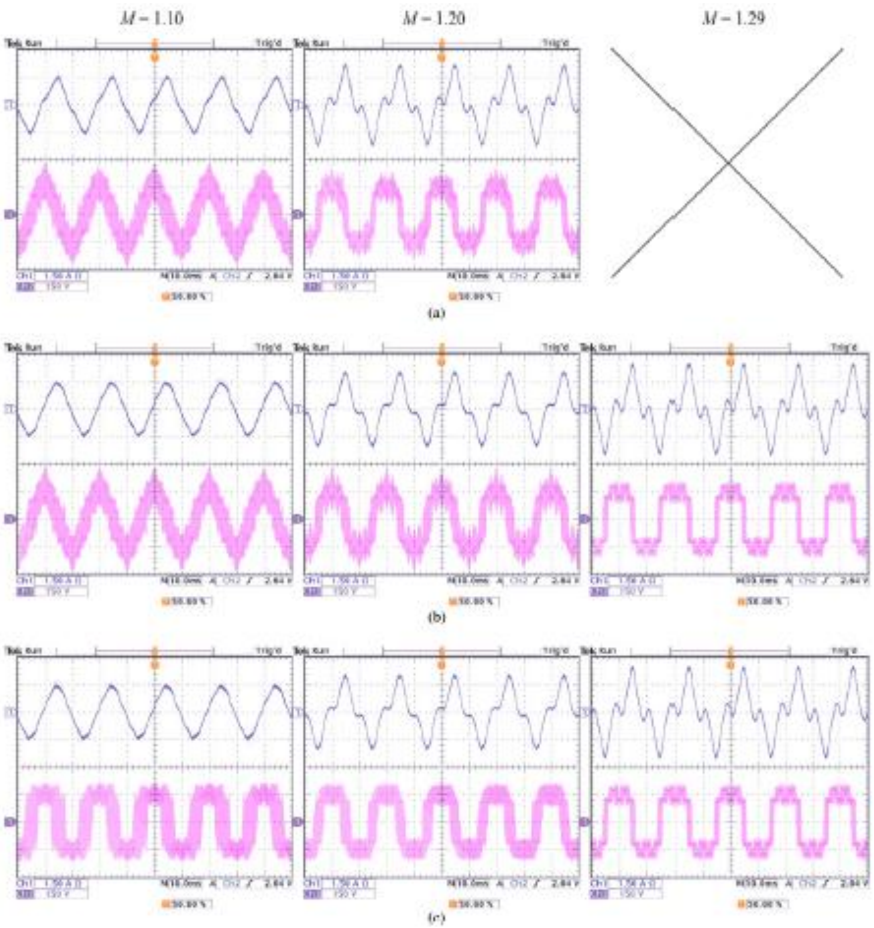
Multiphase machines

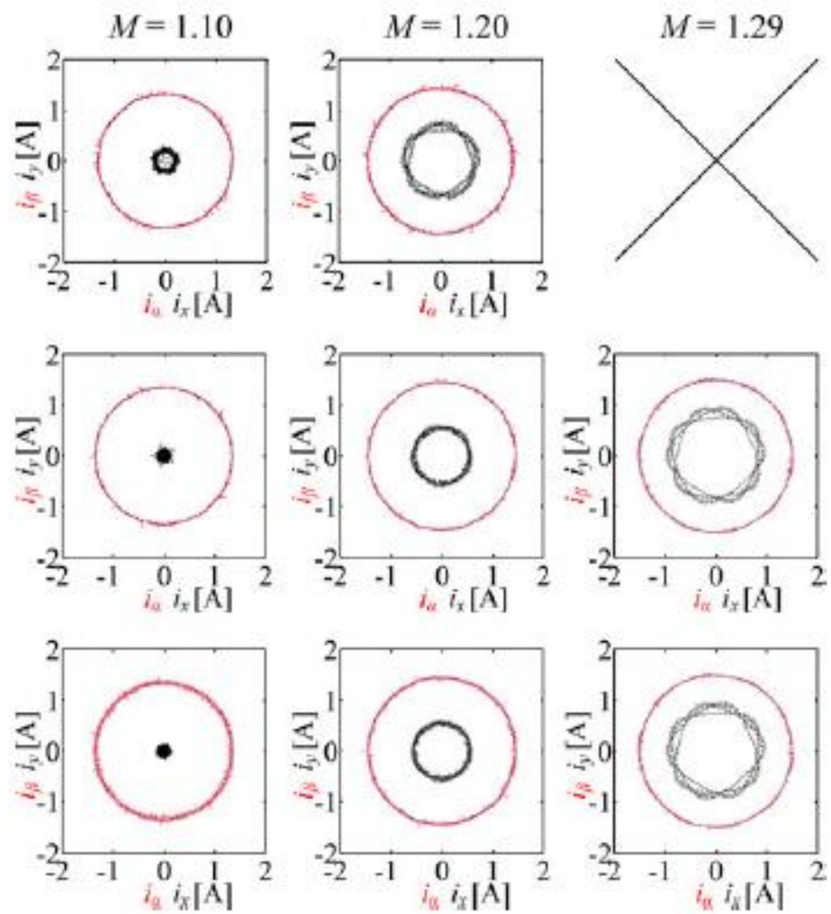
Ways to find equivalencies between CPWM and SVPWM



Multiphase machines

and … What about overmodulation?





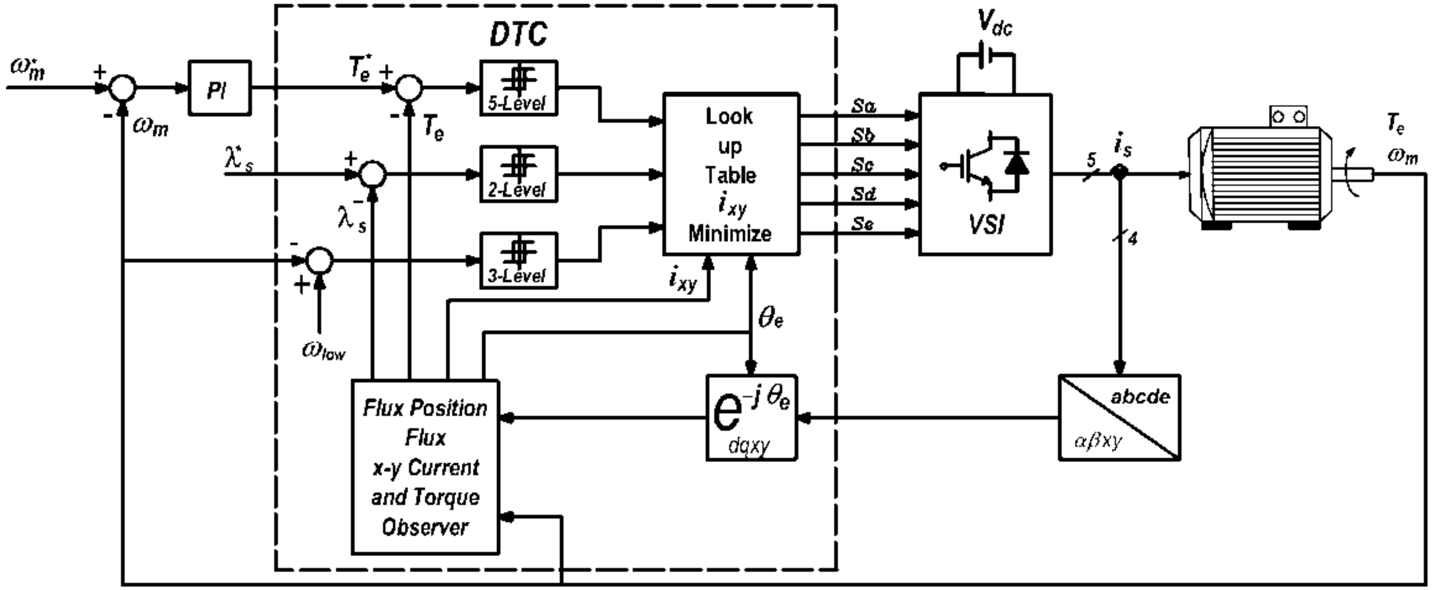
Multiphase machines

Other interesting control methods do not require any modulation technique:

- DTC
- Predictive methods

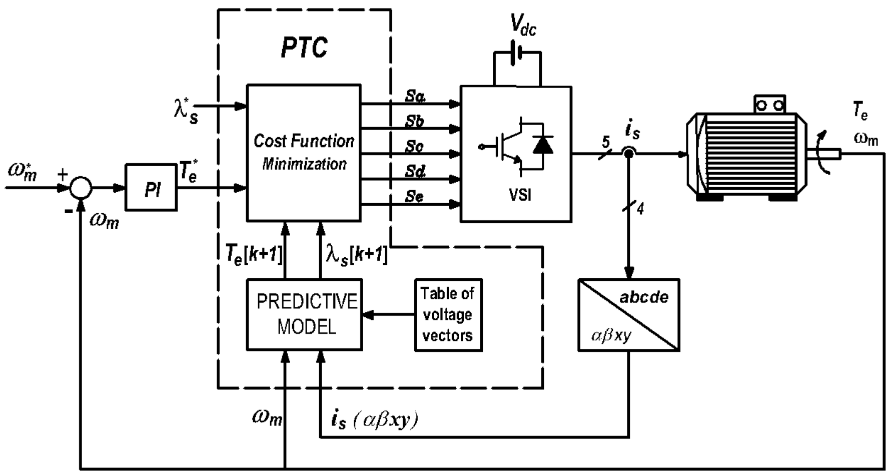
Multiphase machines

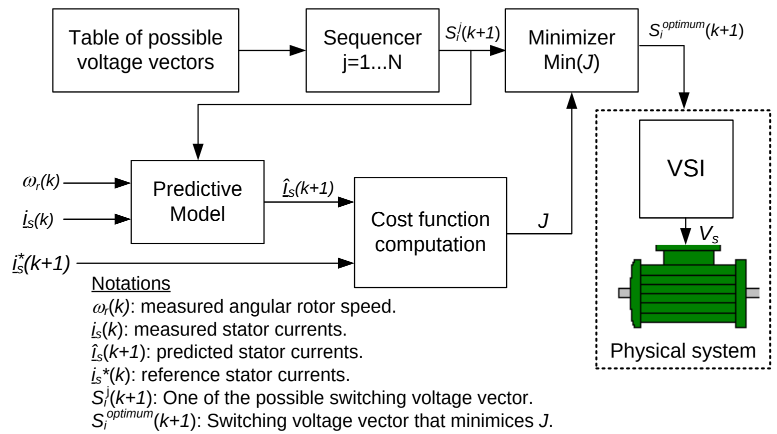
DTC developed for three-phase machines has been extended to multiphase drives …



Multiphase machines

As well as Predictive torque and current control





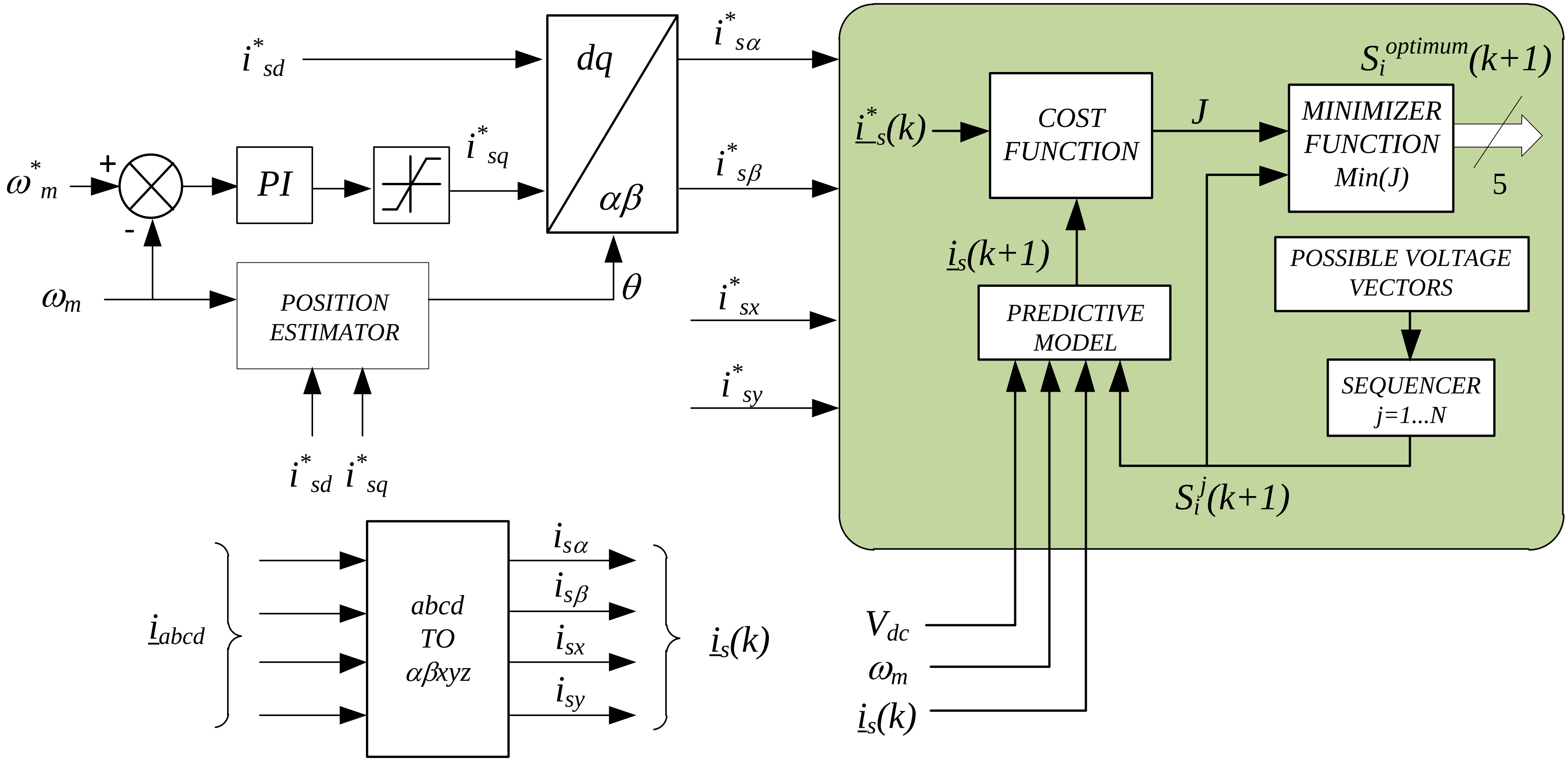
$$J_{\alpha\beta xy} = \left\|\hat{e}_{\alpha\beta}\right\| + \left\|\hat{e}_{xy}\right\|$$

$$\hat{e}_{\alpha\beta} = \frac{\left[i_{\alpha}^{*}(k+1) - \hat{i}_{\alpha}(k+1|k)\right]^{2}}{R_{\alpha\beta}} + \frac{\left[i_{\beta}^{*}(k+1) - \hat{i}_{\beta}(k+1|k)\right]^{2}}{R_{\alpha\beta}}$$

$$\hat{e}_{xy} = \lambda_{xy} \cdot \left[\hat{i}_{x}(k+1|k)^{2} + \hat{i}_{y}(k+1|k)^{2}\right]$$

Multiphase machines

Example of a control scheme with an outer PI-based speed control and inner predictive-based current control.



Conclusions

After some hiccups, MMs have come back to stay

More technological developments are expected to improve their utility

New interesting applications based on them guarantee their final commercial use

i.e. fault tolerant or V2G technology

Multiphase Generators and Drives

Federico Barrero

THANK YOU FOR YOUR ATTENTION