Electric Machine Models in the RTDS Simulator and their Applications

Part II: Poly Phase Machines

Dr. Ali Dehkordi

RTDS Technologies Inc.

Canada

Content of the Presentation

Introduction & Motives for Modeling Poly-Phase Machines

Challenges and a Brief History

Analysis of Poly Phase Synchronous Machines

Developed Models and Simulation Results

Applications

Conclusions

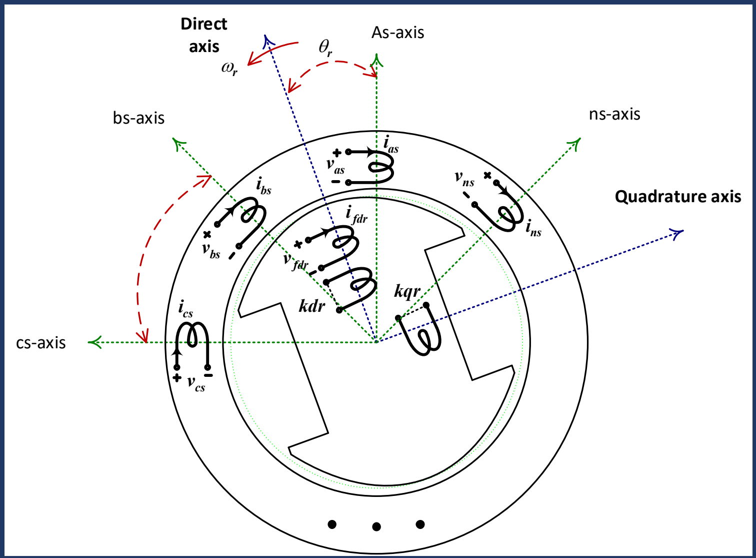
Introduction & Motives for Modeling Poly-Phase Machines

What is a Poly-Phase Machine?

- 3 or More Phases on the Stator or Rotor (up-to 18 or 21)

Types of Poly-Phase Machines

- Symmetrical Displacement
- Split Phase or Multi Stator
- Sets of 3-Phases with no Magnetic Coupling (Mechanical Coupling Through the Shaft)



Introduction & Motives for Modeling Poly-Phase Machines

Advantages of Poly-Phase Machines

- Reduction in Electric Torque Pulsation
- Reliability and Redundancy
- Lower Current Ratings / Phase
- Lower Ratings for Power Electronic Converters
- Noise Characteristics, Copper loss, etc.

Applications of Poly-Phase Machines

- Naval Applications:
  - Submarines, Electric Ships
- New Schemes of Wind Turbines
- Electric Traction
- Electric Vehicles

Introduction & Motives for Modeling Poly-Phase Machines

Why Real-Time?

- Real-time digital simulation is a fully digital simulation where all calculations required to determine the transient state of the power system and servicing of I/Os are completed within a time interval equal to the simulation time-step.
- Simulation results are in synchronism with the real-world clock.
- Real-time response provides the possibility for closed-loop testing of equipment.
- Recent inquiries by customers in the industry motivated us to develop poly-phase machine models.

Challenges of Modeling Poly-Phase Machines

Frame of Reference Solution:
Phase Domain ?

- Challenge of forming the inductance matrix
- Lack of Data
- Computational Burden

Implementation?

- Size of Simulation Time-Step:
  - ➢ Depends on the Application
- Platform:
  - ➢ Processor? FPGA?
- Integration algorithm, saturation, consistency with other models etc.

Challenges of Modeling Poly-Phase Machines

- **A Comprehensive Analysis in Rotor Frame of Reference Seems Necessary for This Research Work.**

- **Question: Is There a DQ Transformation that Applies to Any Number of Phases?**

History

Two Reaction Theory

- Andre Blondel
- Robert E. Doherty
- C. A. Nickle
- Robert H. Park

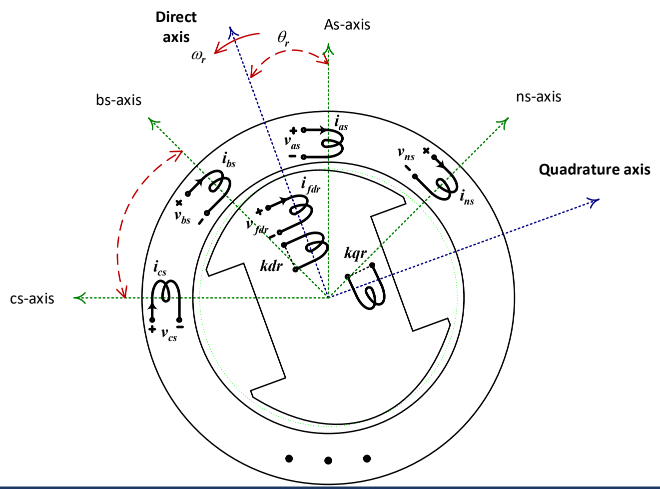
Operational Calculus and Symmetrical Components:

- Oliver Heaviside
- Charles L. Fortescue
- Edith Clarke
- Yu H Ku

Analysis of a Symmetrical Multi-Phase Synchronous Machine

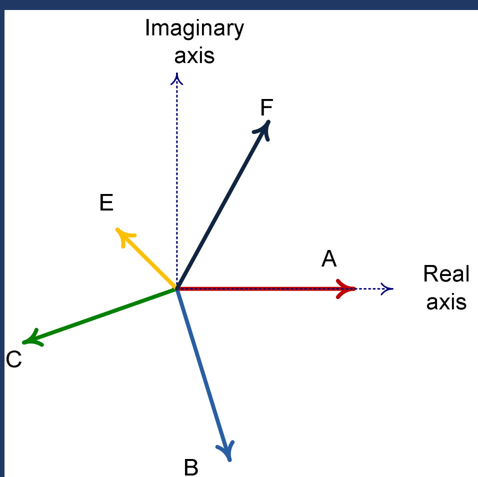
What Are the Goals of Such Analysis?

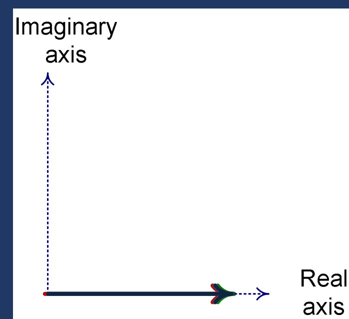
- Understanding the machine and its winding arrangement
- Predict its behaviour
- Equivalent circuit and parameters
- Suitable method for simulation

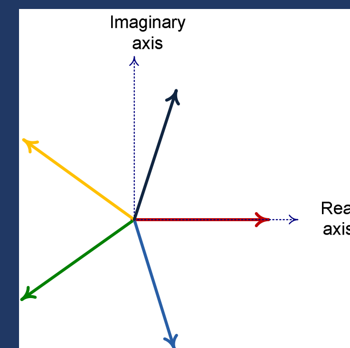


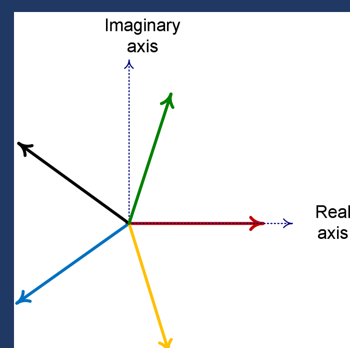
Analysis of a Symmetrical Multi-Phase Synchronous Machine

Symmetrical Components:









…

Analysis of a Symmetrical Multi-Phase Synchronous Machine

Symmetrical Components:

- Symmetry
- Roots of X^N =1
- Any Number of Phases
- Rotation
- Sum of the elements in each row is zero except the first row

$$\alpha = e^{j\delta} \qquad \delta = \frac{2\pi}{N} \qquad \text{N} = \text{Number of Phases}$$

$$\begin{pmatrix} f_0 \\ f_1(f_+) \\ f_2 \\ \vdots \\ f_{\frac{N}{2}} \\ \vdots \\ f_{N-2} \\ f_{N-1}(f_-) \end{pmatrix} = \frac{1}{N} \begin{bmatrix} 1 & 1 & 1 & \dots & 1 & \dots & 1 & 1 \\ 1 & \alpha & \alpha^{2} & \dots & -1 & \dots & \alpha^{N-2} & \alpha^{N-1} \\ 1 & \alpha^{2} & \alpha^{4} & \dots & 1 & \dots & \alpha^{2(N-2)} & \alpha^{2(N-1)} \\ \vdots & \vdots & \vdots & \dots & & \dots & & \\ 1 & -1 & 1 & \dots & & \dots & 1 & -1 \\ \vdots & \vdots & \vdots & \dots & & \dots & & \\ 1 & \alpha^{-2} & \alpha^{(-4)} & \dots & 1 & \dots & \alpha^{(-2)(N-2)} & \alpha^{(-2)(N-1)} \\ 1 & \alpha^{-1} & \alpha^{-2} & \dots & -1 & \dots & \alpha^{(-1)(N-2)} & \alpha^{(-1)(N-1)} \end{bmatrix} \begin{pmatrix} f_A \\ f_B \\ f_C \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \end{pmatrix}$$

Analysis of a Symmetrical Multi-Phase Synchronous Machine

Transformation from Symmetrical Components to General Two-Phase (αβ) For a N-Phase System:

$$
\begin{pmatrix} f_0 \\ f_\alpha \\ f_{u1} \\ \vdots \\ f_w \\ \vdots \\ f_{v1} \\ f_\beta \end{pmatrix}
or
\begin{pmatrix} f_0 \\ f_{\alpha 1} \\ f_{\alpha 2} \\ \vdots \\ f_w \\ \vdots \\ f_{\beta 2} \\ f_{\beta 1} \end{pmatrix}
=
\underbrace{\begin{pmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
 & & & \cdots & & \cdots & & \\
 & & & & 1 & & & \\
 & & & \cdots & & \cdots & & \\
0 & 0 & -j & 0 & 0 & 0 & j & 0 \\
0 & -j & 0 & 0 & 0 & 0 & 0 & j
\end{pmatrix}}_{\left[C_\alpha^1\right]}
\begin{pmatrix} f_0 \\ f_1 (f_+) \\ f_2 \\ \vdots \\ f_{\frac{N}{2}} \\ \vdots \\ f_{N-2} \\ f_{N-1} (f_-) \end{pmatrix}
$$

Analysis of a Symmetrical Multi-Phase Synchronous Machine

Transformation from Phase Quantities to General Two-Phase (αβ) For a N-Phase System:

$$\left[C_\alpha^A\right] = \left[C_\alpha^1\right]\cdot\left[C_1^A\right]$$

$$\begin{pmatrix} f_0 \\ f_\alpha \\ f_{u1} \\ \vdots \\ f_w \\ \vdots \\ f_{v1} \\ f_\beta \end{pmatrix} = \frac{1}{N}\begin{bmatrix} 1 & 1 & 1 & \dots & 1 & \dots & 1 & 1 \\ 2 & 2\cos(\delta) & 2\cos(2\delta) & \dots & \dots & \dots & 2\cos((N-2)\delta) & 2\cos((N-1)\delta) \\ 2 & 2\cos(2\delta) & 2\cos(4\delta) & \dots & 1 & \dots & 2\cos(2(N-2)\delta) & 2\cos(2(N-2)\delta) \\ \vdots & \vdots & \vdots & \dots & & \dots & & \\ 1 & -1 & 1 & \dots & & \dots & 1 & -1 \\ \vdots & \vdots & \vdots & \dots & & \dots & & \\ 0 & 2\sin(2\delta) & 2\sin(4\delta) & \dots & 1 & \dots & 2\sin(2(N-2)\delta) & 2\sin(2(N-2)\delta) \\ 0 & 2\sin(\delta) & 2\sin(2\delta) & \dots & -1 & \dots & 2\sin((N-2)\delta) & 2\sin((N-1)\delta) \end{bmatrix}\begin{pmatrix} f_A \\ f_B \\ f_C \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \end{pmatrix}$$

$$\begin{pmatrix} f_d \\ f_q \end{pmatrix} = \begin{pmatrix} \cos(\theta_r) & \sin(\theta_r) \\ -\sin(\theta_r) & \cos(\theta_r) \end{pmatrix}\begin{pmatrix} f_\alpha \\ f_\beta \end{pmatrix}$$

- **In some conventions the signs are reversed**

Analysis of a Symmetrical Multi-Phase Synchronous Machine

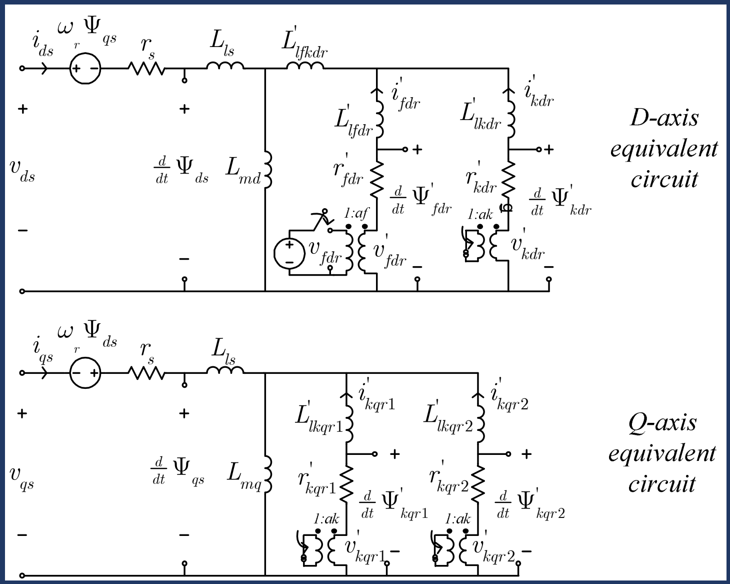
Application of DQ Transformation to the Phase-Domain Inductance Matrix of a N-Phase Machine Assuming Sinusoidal Distribution of the Windings and Permeance:

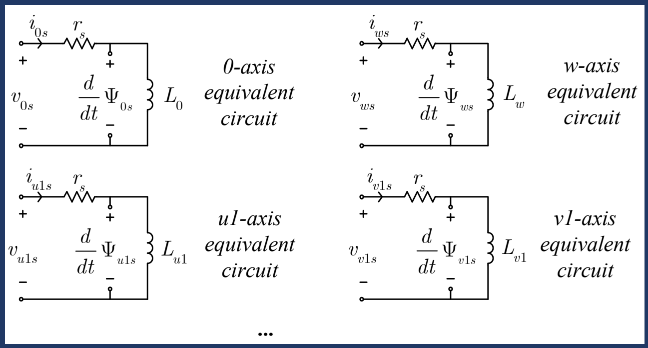
- The proposed DQ transformation diagonalizes the inductance matrix of the machine.
- An equivalent circuit can be achieved in DQ frame of reference with multiple zero sequence circuits.

$$\left[L_{dq}\right]=\begin{bmatrix} L_{ls} & 0 & 0 & \dots & 0 \\ 0 & L_{ls}+M_{os}+L_{2s} & 0 & \dots & 0 \\ 0 & 0 & L_{ls} & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & \dots & L_{ls}+M_{os}-L_{2s} \end{bmatrix}$$

Analysis of a Symmetrical Multi-Phase Synchronous Machine

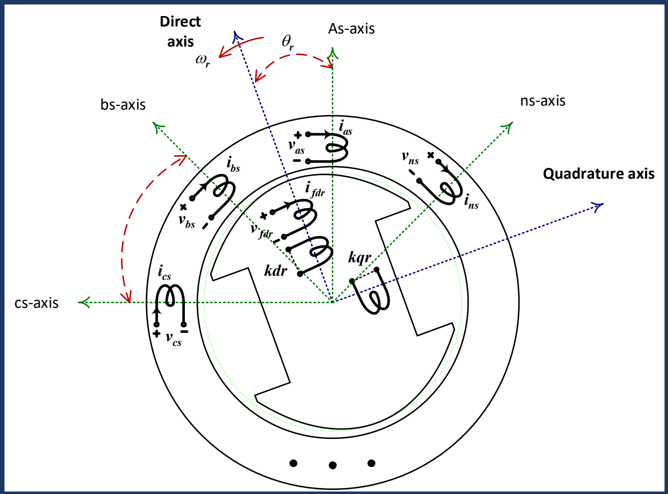
DQ Equivalent Circuit of a Symmetrical Multi-Phase Synchronous Machine:



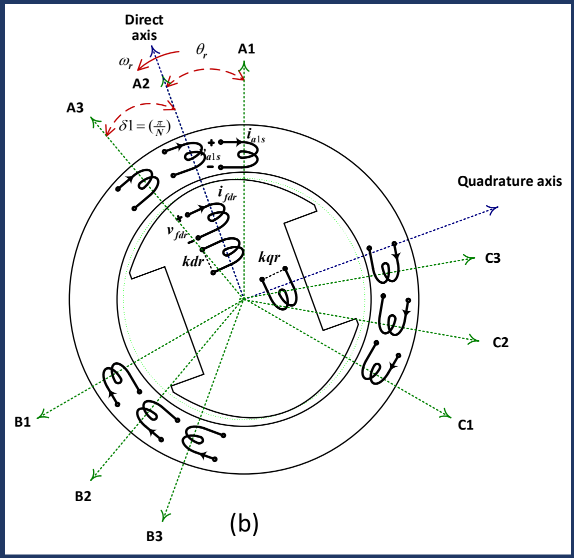


Analysis of a Multi-Star Synchronous Machine

Symmetrical
Multi-Phase



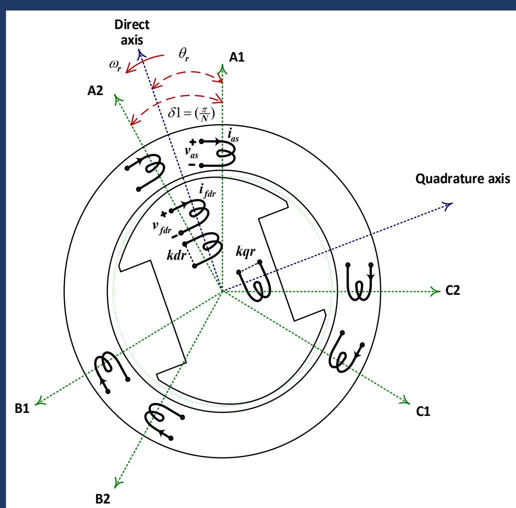
Multi-Star



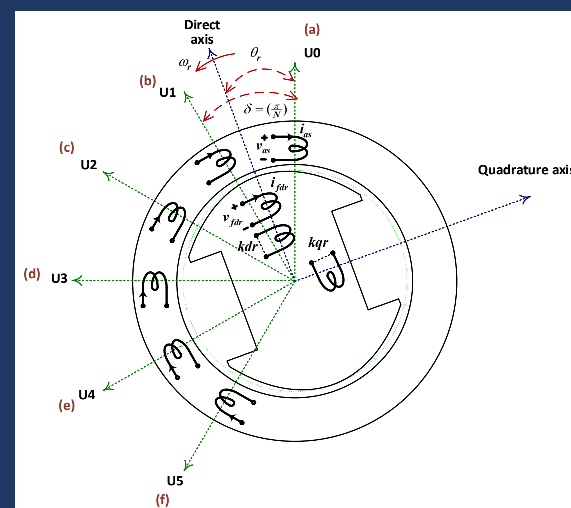
Analysis of a Multi-Star Synchronous Machine

Multi-Star Winding Configuration and Transformation to Fundamental Winding Configuration (180° Phase Progression)

- *l* winding sets (stars) with *k* phases for each winding, angular displacement = *π/N*



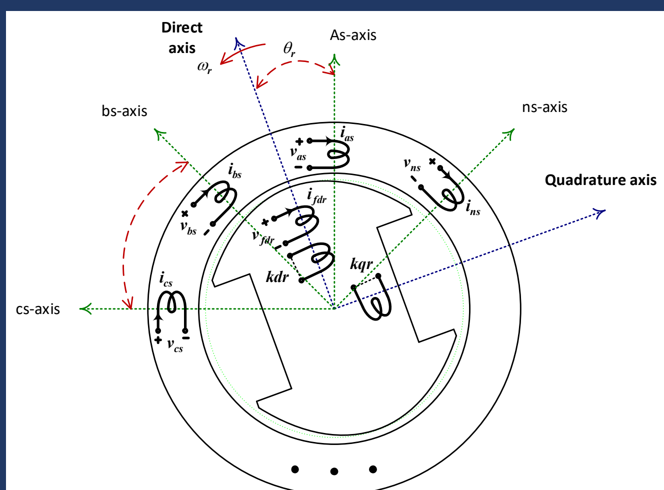
$$[W_{2\times3}] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$



Analysis of a Multi-Star Synchronous Machine

360° Phase Progression of Windings or two-pole symmetry

- Fortescue's Symmetrical Component Transformation



180° Phase Progression of Windings or single-pole symmetry

- A New Symmetrical Component Transformation for 180° Phase Progression

$$\left(f_{\alpha 1}\ f_{\alpha 3}\ f_{\alpha 5}\ f_{\beta 5}\ f_{\beta 3}\ f_{\beta 1}\right)^T = C_\alpha^a \cdot \left(f_a\ f_b\ f_c\ f_d\ f_e\ f_f\right)^T$$

where:

$$\left[C_\alpha^a\right] = \left[J^{-1}\right] = \left(\frac{2}{N}\right) \cdot \begin{bmatrix} 1 & \cos(\delta 1) & \cos(2\delta 1) & \cos(3\delta 1) & \cos(4\delta 1) & \cos(5\delta 1) \\ 1 & \cos(3\delta 1) & \cos(6\delta 1) & \cos(9\delta 1) & \cos(12\delta 1) & \cos(15\delta 1) \\ 1 & \cos(5\delta 1) & \cos(10\delta 1) & \cos(15\delta 1) & \cos(20\delta 1) & \cos(25\delta 1) \\ 0 & \sin(5\delta 1) & \sin(10\delta 1) & \sin(15\delta 1) & \sin(20\delta 1) & \sin(25\delta 1) \\ 0 & \sin(3\delta 1) & \sin(6\delta 1) & \sin(9\delta 1) & \sin(12\delta 1) & \sin(15\delta 1) \\ 0 & \sin(\delta 1) & \sin(2\delta 1) & \sin(3\delta 1) & \sin(4\delta 1) & \sin(5\delta 1) \end{bmatrix}$$

$$\delta 1 = \frac{\pi}{6}$$

Analysis of a Multi-Star Synchronous Machine

Treatment of Leakage Inductance Matrix

- Application of symmetrical component or αβ transformations with 180° phase progression diagonalizes the Toeplitz-structured leakage inductance matrix

$$\left[L_{ss-l}\right] = \begin{bmatrix} l_0 & l_1 & l_2 & \cdots & -l_3 & -l_2 & -l_1 \\ l_1 & l_0 & l_1 & \cdots & -l_4 & -l_3 & -l_2 \\ l_2 & l_1 & l_0 & \cdots & -l_5 & -l_4 & -l_3 \\ \cdots & \cdots & \cdots & & \cdots & \cdots & \cdots \\ -l_3 & -l_4 & -l_5 & \cdots & l_0 & l_1 & l_2 \\ -l_2 & -l_3 & -l_4 & \cdots & l_1 & l_0 & l_1 \\ -l_1 & -l_2 & -l_3 & \cdots & l_2 & l_1 & l_0 \end{bmatrix}$$

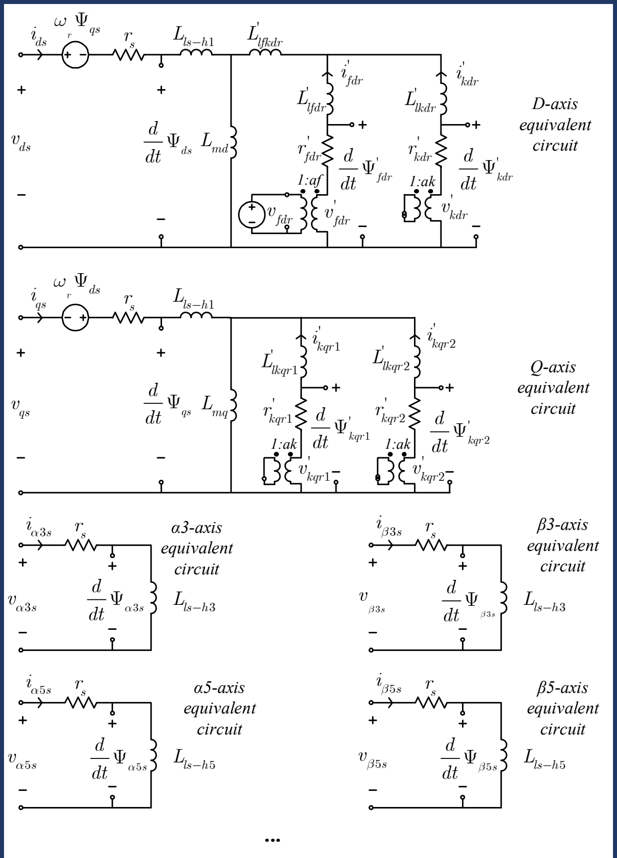
$$\left[L_{ss-l}\right]^{dq} = \begin{bmatrix} L_{ls-h1} & 0 & 0 & \cdots & 0 & 0 & 0 \\ 0 & L_{ls-h3} & 0 & \cdots & 0 & 0 & 0 \\ 0 & 0 & L_{ls-h5} & \cdots & 0 & 0 & 0 \\ \cdots & \cdots & \cdots & L_{ls-hm} & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & L_{ls-h5} & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & L_{ls-h3} & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & L_{ls-h1} \end{bmatrix}$$

$$L_{ls-hm} = l_0 + 2 \cdot \sum_{k=1}^{truc\left(\frac{N-1}{2}\right)} l_k \cdot \cos(m \cdot k \cdot \delta 1)$$

Analysis of a Multi-Star Synchronous Machine

Equivalent Circuit in DQ frame of Reference

- Additional zero sequence circuits
- A homo-polar zero sequence circuit with odd number of phases

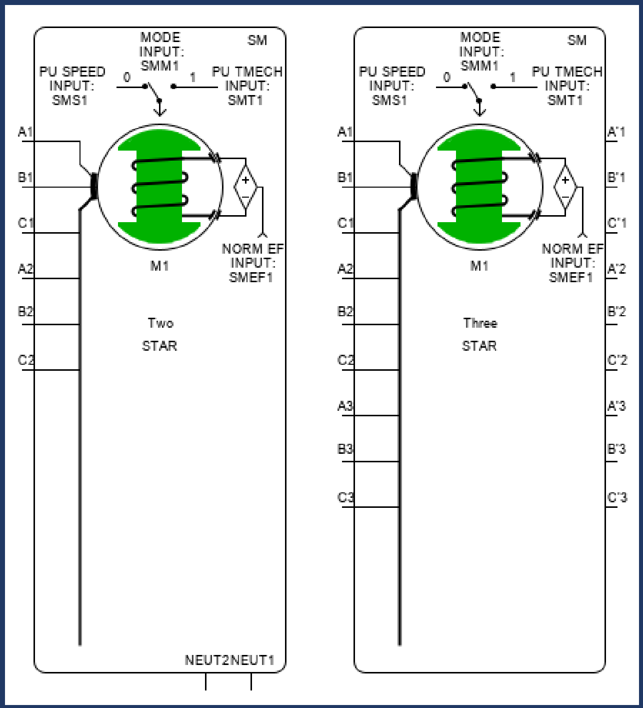


Developed Models and Simulation Results

Features and Capabilities of the Model

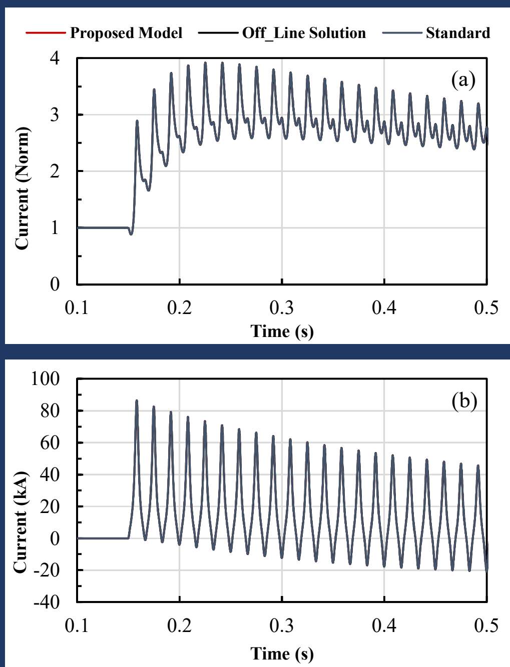
- Up to 4-star synchronous machine model with 3-phase stars
- Implemented in both main and substep
- Access to multiple neutrals or all winding ends

Number of Phase	3	6	9	12
Execution Time (ns)	446	690	997	1330

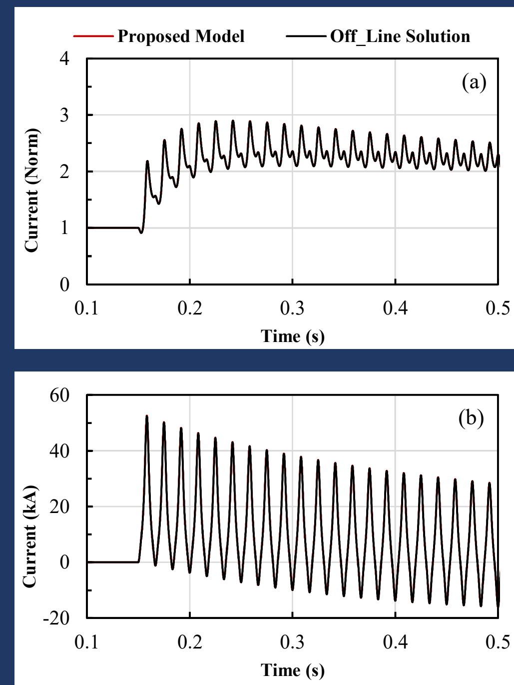


Developed Models and Simulation Results

3-Phase Mac, Single-Phase Fault:

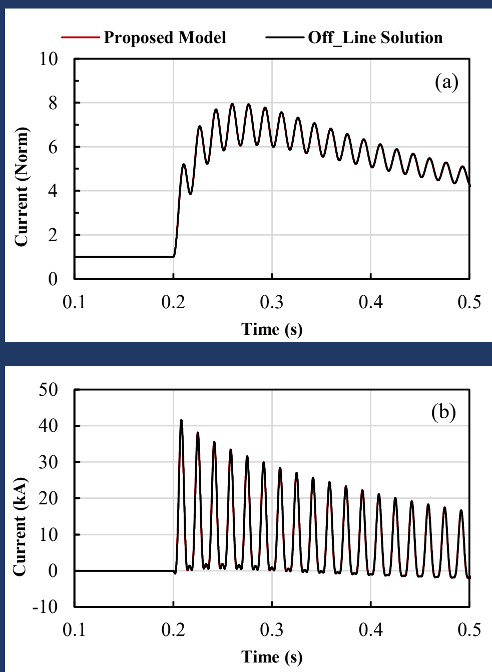


5-Phase Mac, Single-Phase Fault :

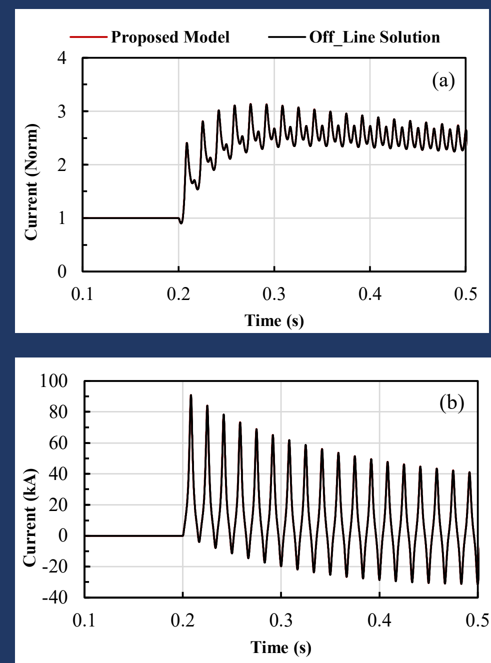


Developed Models and Simulation Results

2-Star Mac, 6-Phase Fault:



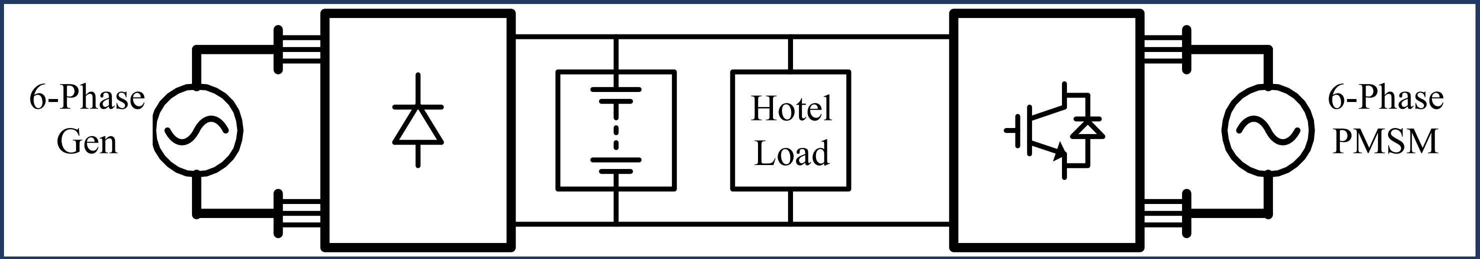
3-Star Mac, Single-Phase Fault:



Developed Models and Simulation Results

Application Example:

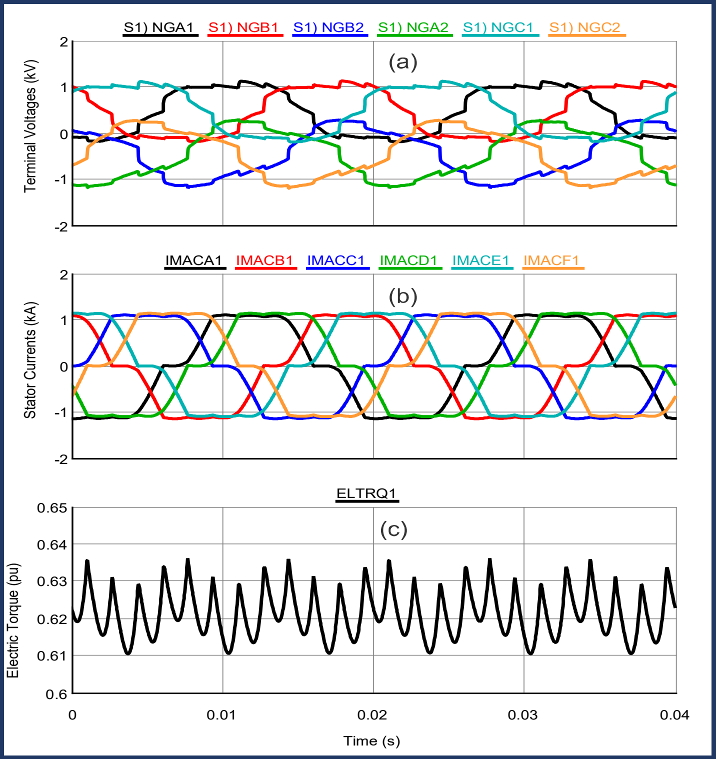
- A typical electric network of a marine vessel consisting of:
  - A dual star generator and rectifiers
  - A DC bus
  - Battery storage and hotel load
  - Propulsion system, a dual star PMSM and two 3-phase converters



Developed Models and Simulation Results

Performance of the Multi-Star Generator in Steady-State:

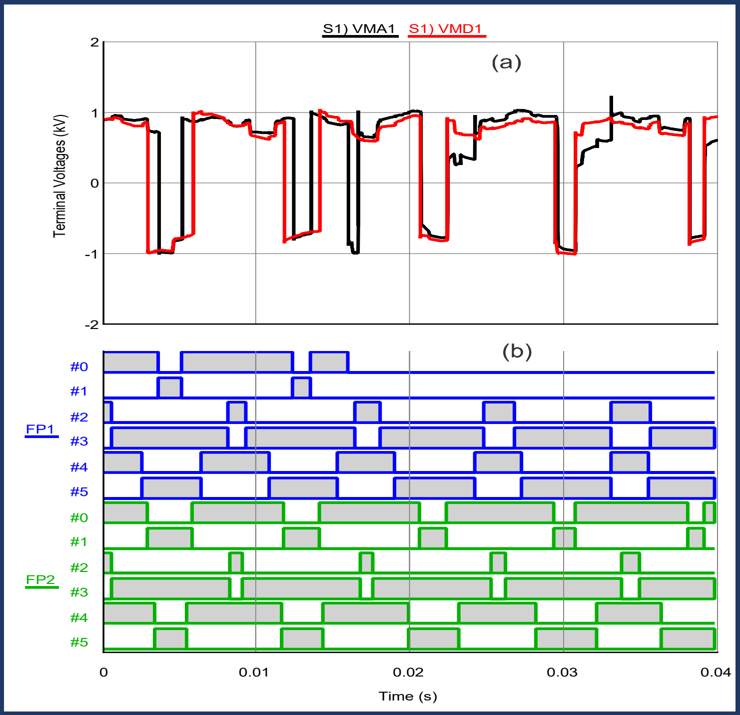
- Generator currents represent the dual star arrangement
- Electric torque contains the 12th harmonic component



Developed Models and Simulation Results

Performance of the Motor Drive System during the Loss of a Converter Leg:

- PMSM is supplied through two 3-phase converters
- The gating signals to phase A of converter 1 are suddenly blocked.
- The variations of voltages are shown.
- Drive system can maintain the speed even with the loss of a few converter legs.



Conclusions

Based on a Generalized Method of Vector Space Decomposition (VSD), Analysis of Symmetrical Poly-Phase and Multi-Star Synchronous Machines is Presented.

Detailed and Flexible Transient Poly-Phase Synchronous Machine Model are Developed and Validated for Electromagnetic Transient Program and Real-Time Digital Simulation.

A Typical Power System Circuit of a Marine Vessel is Simulated using the Introduced Models. The Implementation is Similar to that of a Wind Turbine with such Machines.

Demonstration of A Typical Power System Circuit of a Marine Vessel Simulated using the Introduced Models

Thank you!

www.rtds.com

Contact us: dehkordi@rtds.com

RTDS Technologies