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Work: **A Multi-Star Synchronous Machine Model for Real-Time Digital Simulation and Its Applications**

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# Content of the Presentation

Introduction & Motives for Modeling Poly-Phase Machines

Analysis of a Multi-Star Synchronous Machine

Developed Models and Simulation Results

Conclusions

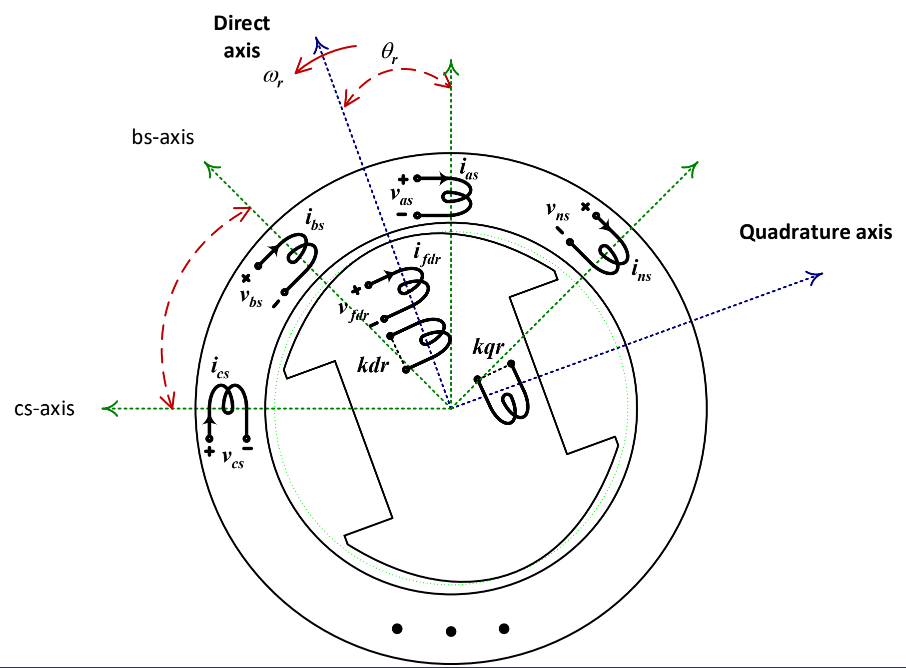
# Introduction & Motives for Modeling Poly-Phase Machines

## 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
- Traction
- Electric Vehicles

# Introduction & Motives for Modeling Poly-Phase Machines

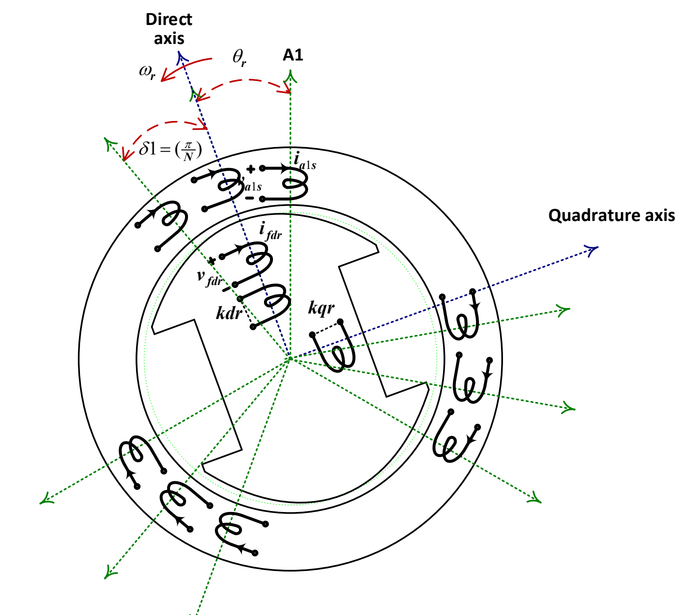
## Why Real-Time?

- 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 multi-star machine models.

# Analysis of a Multi-Star 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

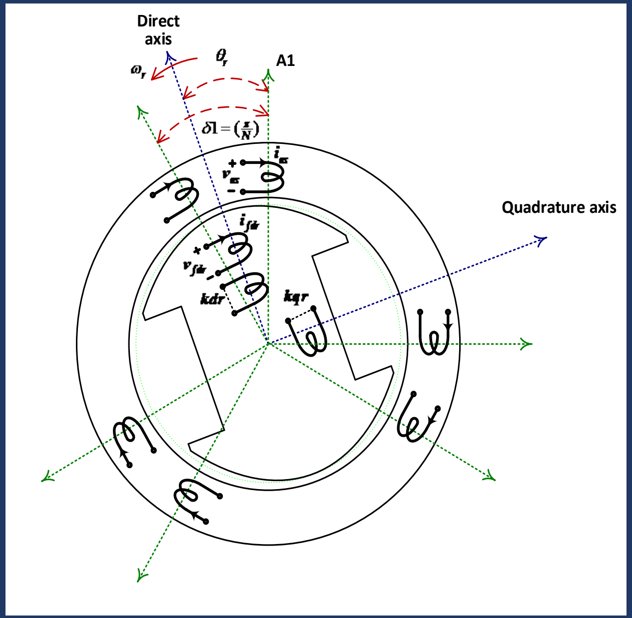



(b)

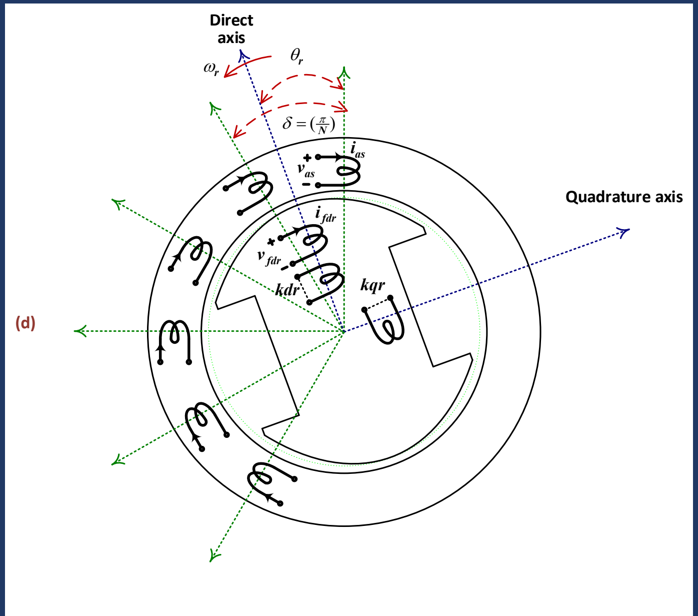
# Analysis of a Multi-Star Synchronous Machine

## 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*



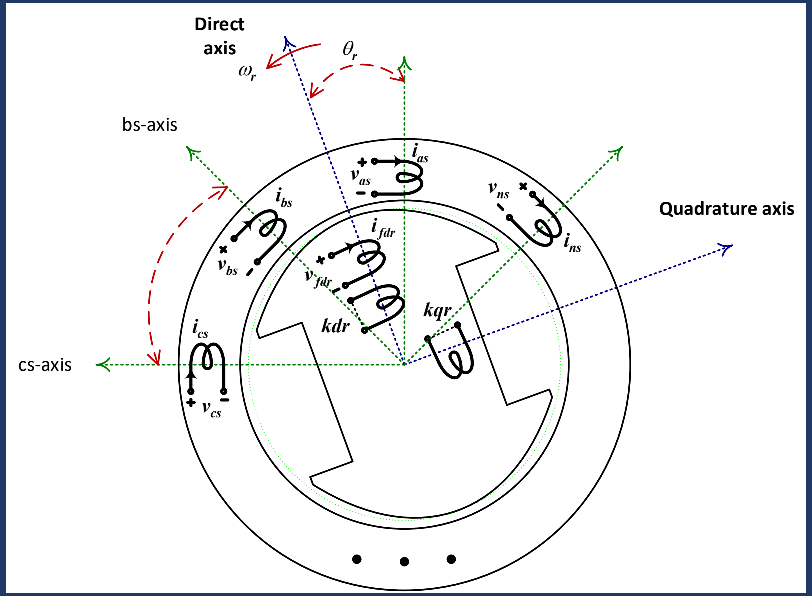

$$W_{2\times 3} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$



# 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

$$\begin{bmatrix} f_{1} & f_{3} & f_{5} & f_{5} & f_{3} & f_{1} \end{bmatrix}^T = C^a \begin{bmatrix} f_a & f_b & f_c & f_d & f_e & f_f \end{bmatrix}^T$$

where:

$$C^a = J^{-1}\sqrt{\frac{2}{N}}\begin{bmatrix} 1 & \cos(\theta_1) & \cos(2\theta_1) & \cos(3\theta_1) & \cos(4\theta_1) & \cos(5\theta_1) \\ 1 & \cos(3\theta_1) & \cos(6\theta_1) & \cos(9\theta_1) & \cos(12\theta_1) & \cos(15\theta_1) \\ 1 & \cos(5\theta_1) & \cos(10\theta_1) & \cos(15\theta_1) & \cos(20\theta_1) & \cos(25\theta_1) \\ 0 & \sin(5\theta_1) & \sin(10\theta_1) & \sin(15\theta_1) & \sin(20\theta_1) & \sin(25\theta_1) \\ 0 & \sin(3\theta_1) & \sin(6\theta_1) & \sin(9\theta_1) & \sin(12\theta_1) & \sin(15\theta_1) \\ 0 & \sin(\theta_1) & \sin(2\theta_1) & \sin(3\theta_1) & \sin(4\theta_1) & \sin(5\theta_1) \end{bmatrix}$$

$$\theta_1 = \frac{\pi}{6}$$

# 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

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

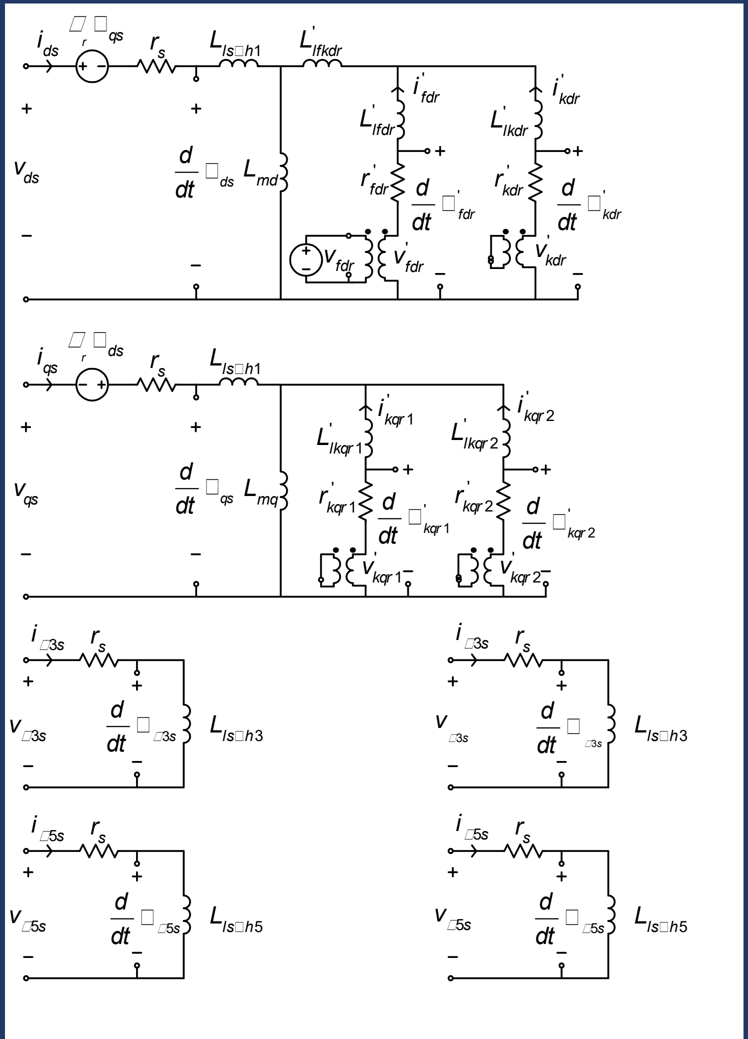
$$
\left[L_{ss-l}\right]^{dq}=\begin{bmatrix}
L_{ls-h1} & 0 & 0 & \cdots & 0 & 0 & 0 \\
0 & L_{ls-h3} & 0 & \cdots & 0 & 0 & 0 \\
0 & 0 & L_{ls-h5} & \cdots & 0 & 0 & 0 \\
\vdots & \vdots & \vdots & L_{ls-hm} & \vdots & \vdots & \vdots \\
0 & 0 & 0 & \cdots & L_{ls-h5} & 0 & 0 \\
0 & 0 & 0 & \cdots &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

$$
L_{ls-hm}=l_0+2\cdot\sum_{k=1}^{truc\left(\frac{N-1}{2}\right)} l_k\cdot\cos(m\cdot k\cdot d1)
$$

# 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

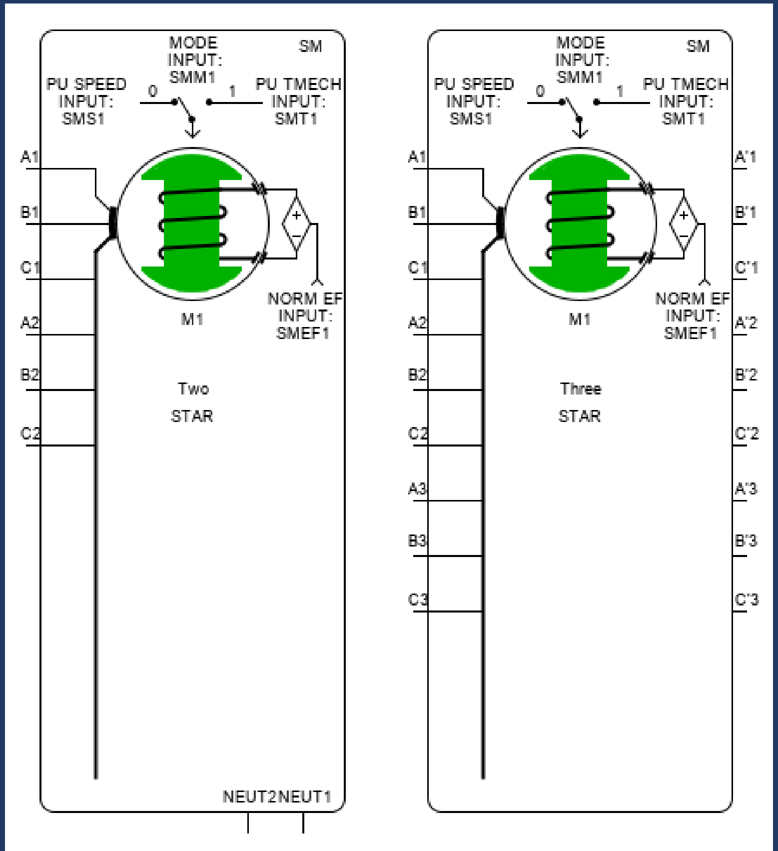


# Developed Models and Simulation Results

## Features and Capabilities of the Model

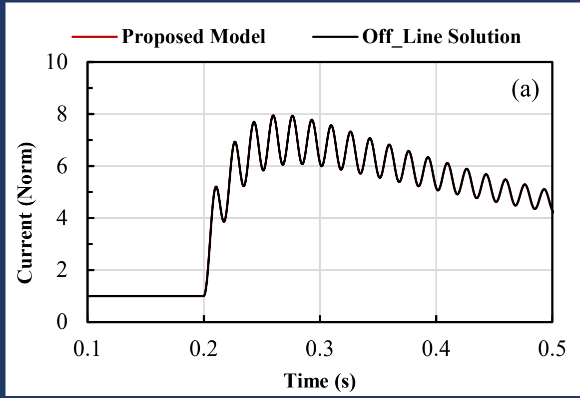
- Up to 4-star synchronous machine model with 3-phase stars
- Implemented in both main and substep
- Access to multiple neutrals or all winding ends

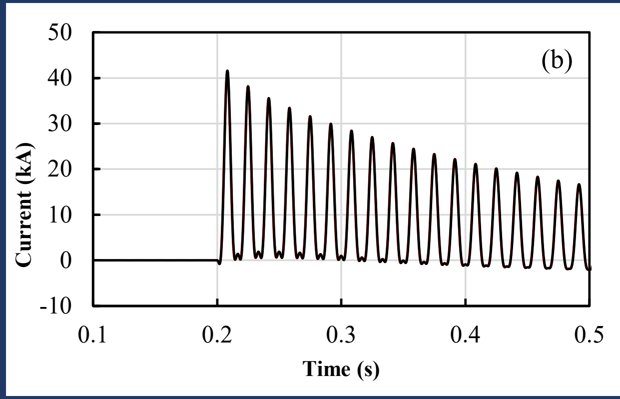
| Number of Phase | 3 | 6 | 9 | 12 |
|---|---|---|---|---|
| Execution Time (ns) | 446 | 690 | 997 | 1330 |



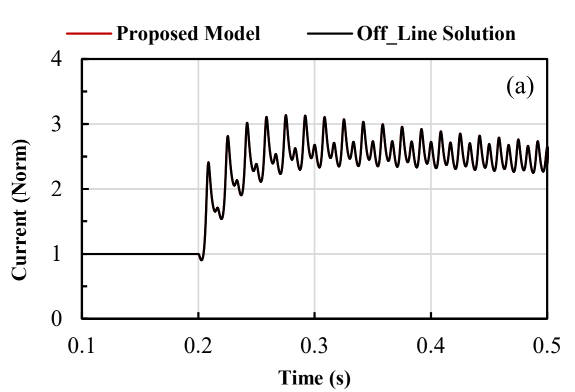
# Developed Models and Simulation Results

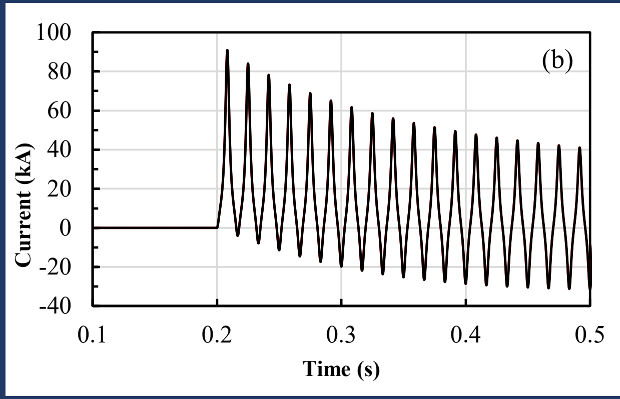
## 2-Star Mac, 6-Phase Fault:




## 3-Star Mac, Single-Phase Fault:

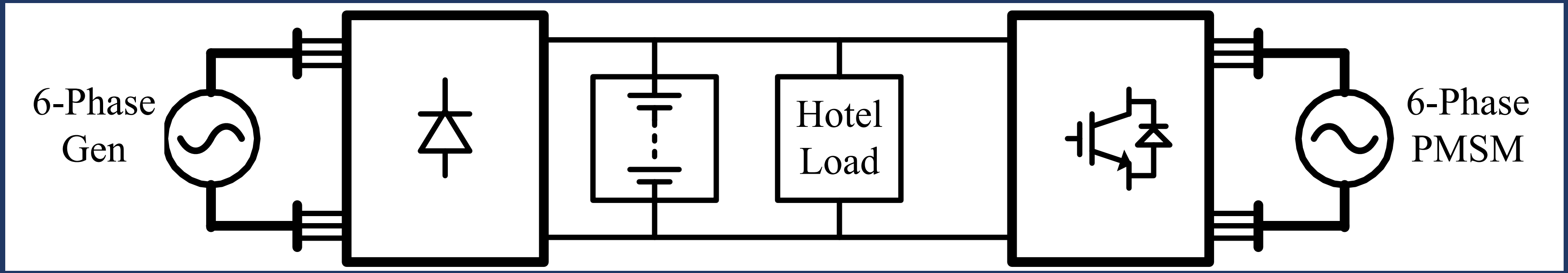


# Developed Models and Simulation Results

## 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 Multi-Star Synchronous Machines is Presented

A Detailed and Flexible Transient Multi-Star Synchronous Machine Model is 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 Model. The Implementation is Similar to that of a Wind Turbine with such Machines

# Thank you!

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