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# Digital Twins of Different Types Electrical Machines

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**Abstract**
This paper aims to address key considerations in building digital twins for some of the most commonly used electrical machines, including the Induction Machine with a Squirrel Cage Rotor, DC Machine with Linear Electrical Excitation, DC Machine with Permanent Excitation, Synchronous Machine with Electrical Excitation and Damper, and Synchronous Machine with Permanent Excitation and Damper. These machines, critical across various industries, require precise modeling and real-time monitoring to optimize their performance and lifespan. The development of digital twins for these machines involves creating virtual representations that dynamically mirror their physical counterparts, using real-time data from sensors and advanced simulation techniques. Each machine type presents unique challenges for the digital twin, such as accurately capturing the electromagnetic interactions in the squirrel cage rotor or modeling the excitation systems in synchronous and DC machines. This paper investigates the methodologies for overcoming these challenges, focusing on data acquisition, mathematical modeling, real-time analytics, and predictive diagnostics. The paper also highlights the benefits of digital twin technology, including enhanced operational efficiency, reduced downtime through predictive maintenance, and optimized control under varying load conditions. Additionally, it discusses the integration of digital twins into broader Industrial Internet of Things (IIoT) frameworks, paving the way for more connected and autonomous industrial environments. The findings in this paper provide valuable insights for both researchers and engineers seeking to implement digital twins in electrical machine systems, contributing to improved industrial automation and machine lifecycle management.

## INTRODUCTION

The concept of digital twins has gained significant traction across various industries, offering new possibilities for the real-time monitoring, simulation, and optimization of physical assets. A digital twin is a virtual representation of a physical object, system, or process that mirrors its real-world counterpart through data integration and advanced analytics. This technology provides a dynamic interface between the physical and digital worlds, enabling engineers and operators to predict performance, diagnose issues, and optimize operations more effectively [1–3].

In the domain of electrical motors, the implementation of digital twins holds immense potential. Electrical motors are ubiquitous in modern industry, powering critical processes in sectors such as manufacturing, transportation, and energy production. Given their widespread use, optimizing the performance, reliability, and maintenance of these machines is crucial to ensuring efficiency and minimizing downtime. Digital twins of electrical motors provide a powerful tool to achieve these objectives by enabling continuous monitoring, predictive maintenance, and enhanced fault diagnostics [4–6].

This paper explores the development and application of digital twins for electrical motors. It examines the key components required for creating accurate and effective digital models, including data acquisition, simulation techniques, and real-time feedback loops. Additionally, the paper discusses the potential benefits of employing digital twins in the context of electric motors, such as reduced operational costs, improved system reliability, and extended machine life. Through a detailed analysis of the state-of-the-art technologies and methodologies, this paper aims to highlight the transformative role that digital twins can play in the management and optimization of electrical motors.

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Furthermore, it offers insights into future research directions and the challenges that need to be addressed for the widespread adoption of digital twin technology in the electrical motor industry.

For all types of electrical machines there are common features: data acquisition and sensors, stage of mathematical modeling and simulation, using machine learning and predictive analytics to predict motor parameters depend on ordinary and critical working modes, real-time monitoring and feedback, building and implementing control systems and optimization [5–8].

For an effective digital twin, real-time data collection is critical. Various sensors must be embedded in the physical motor to gather data such as:

- temperature of windings and bearings;
- vibration levels;
- voltage and current characteristics;
- rotational speed and torque;
- motor slip and efficiency.

These data points form the foundation of the digital twin, enabling a dynamic and constantly updated digital representation of the motor's condition.

The behavior of an induction motor can be described through well-known mathematical models based on electrical and mechanical principles. the squirrel cage rotor, in particular, has specific operational characteristics, including non-linear current-voltage relationships; complex electromagnetic interactions in the rotor bars and stator windings; torque-slip characteristics and speed-torque curves.

The digital twin incorporates these models to simulate the motor's behavior under varying operating conditions, allowing engineers to predict responses to different load demands, ambient conditions, and system configurations.

In combination with traditional physics-based models, advanced analytics and machine learning algorithms can be integrated into the digital twin to detect patterns and anomalies that may indicate future failures or operational inefficiencies. This aspect of the digital twin enables predictive maintenance, where machine learning can forecast issues like rotor bar failures, bearing wear, or insulation degradation before they cause a breakdown, minimizing unexpected downtimes.

The digital twin enables real-time monitoring by processing incoming sensor data and comparing it with the expected performance based on the motor's current operational mode. Deviations from normal operating conditions can be immediately detected, allowing the system to issue warnings or automatically adjust parameters to maintain performance. For example, the twin might identify unusual heat generation in the rotor, which could indicate an imbalance or early-stage failure in the rotor bars or bearings.

In addition to monitoring and diagnostics, digital twins can contribute to the real-time optimization of motor performance. By analyzing the operational data, a digital twin can recommend optimal control settings, such as adjusting the power supply, torque, or speed to maximize efficiency or minimize energy consumption under varying load conditions. This optimization can reduce energy costs, improve motor efficiency, and extend the life of the motor's components.

The aim of this paper is to disclose questions connected with building digital twins of commonly used electrical machines: Induction Machine with Squirrel Cage Rotor, DC Machine Linear Electrical Excitation, DC Machine Permanent Excitation, Synchronous Machine Electrical Excitation with Damper and Synchronous Machine Permanent Excitation with Damper [9]. The challenges associated with building digital twins for these machines stem from the complexity of their physical behavior and the need for accurate modeling. Each type of electrical machine presents unique demands for data acquisition, simulation accuracy, and real-time feedback. For instance, the induction machine requires precise modeling of rotor bar behavior under various load conditions, while synchronous machines with dampers necessitate complex simulations to account for their dynamic response during transient conditions. Addressing these challenges involves combining advanced mathematical models with machine learning algorithms and real-time data analytics to create robust digital twins that can adapt to different operational scenarios [10–12].

## INDUCTION MACHINE WITH SQUIRREL CAGE ROTOR

Induction machines, particularly those with squirrel cage rotors, are among the most commonly used types of electric motors in industrial applications due to their robustness, efficiency, and relatively simple construction [11–12]. The squirrel cage induction motor (SCIM) is especially popular in applications requiring reliable and low-maintenance motors, such as in manufacturing processes, transportation systems, and various types of heavy machinery. However, like all machinery, SCIMs are subject to wear, efficiency losses, and potential failure over time. This is where the concept of digital twins can bring substantial benefits. A digital twin of an induction machine with a squirrel cage rotor is a precise virtual model that replicates the motor's physical state and operational behavior in real time. By continuously receiving and processing data from sensors embedded in the motor, the digital twin can provide insights into the machine's health, performance, and operational efficiency.

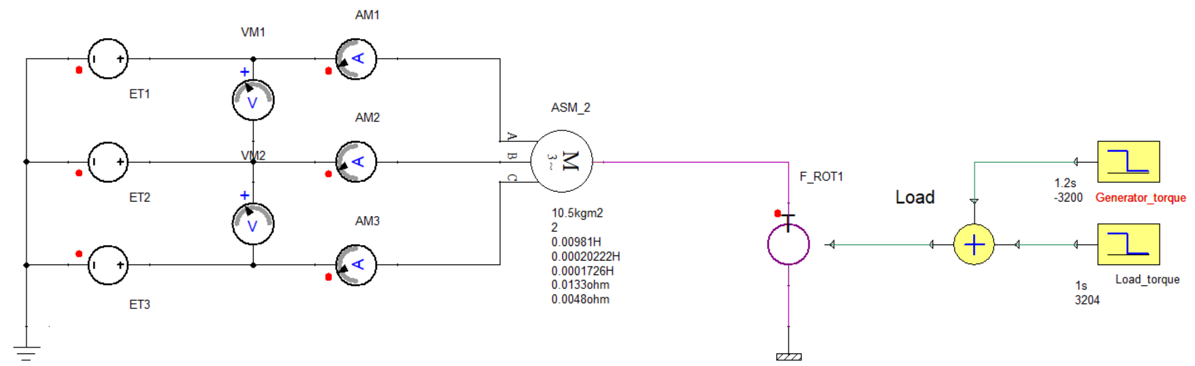


**Figure 1.** Simulation model of induction motor in ANSYS Twin Builder

This real-time mirroring allows for predictive diagnostics, dynamic optimization, and improved maintenance scheduling, ultimately enhancing the lifespan and efficiency of the motor [13–17].

In this example (Fig. 1), the Induction Machine ASM_2 is connected to a to a three-phase power supply composed of Sinusoidal Voltage Sources ET1, ET2 and ET3. The mechanical terminal of ASM_2 is connected to a Torque Source F_ROT1, whose torque value is decided by the summation of the outputs of the Step Functions Generator_torque and Load_torque.

The model represents an induction machine with squirrel cage rotor and star-connected stator windings as a lumped circuit component. The circuit nodes A-B-C are the terminals of star-connected stator windings. Due to its rotational pin, the machine can be connected to mechanical components from the physical domains folder. This component cannot be used with AC and DC simulation.

Model Limits of Induction Machine Model:

- 3-phase symmetrical induction machine with squirrel cage rotor and star-connected stator wingdings without neutral node (no zero phase-sequence system);
- linear and iron-loss free magnetic circuit;
- no consideration of skin effects in the wingdings (restricted simulation accuracy at e.g. start-up processes; typical case: current-displacement motor connected to the mains);
- exclusive consideration of fundamental flux linkage between stator and rotor wingdings;
- rotor position-independent leakage inductances;
- friction losses (parasitic torques) are not considered in the model; they can be added with the load torque parameter externally.

The equation system is implemented in a stator-fixed coordinate system (α-β coordinates). Index 1 represents the stator quantities, index 2 the rotor quantities. The phase quantities of the real three-phase induction machine are indicated with a, b, c. Ψ is the magnetic flux. The simulation results are shown in Fig. 2–4.

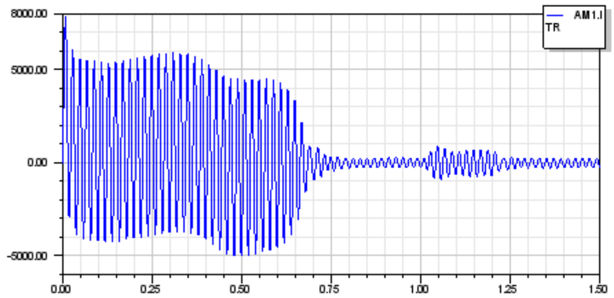


**Figure 2.** Simulation of induction motor: phase current

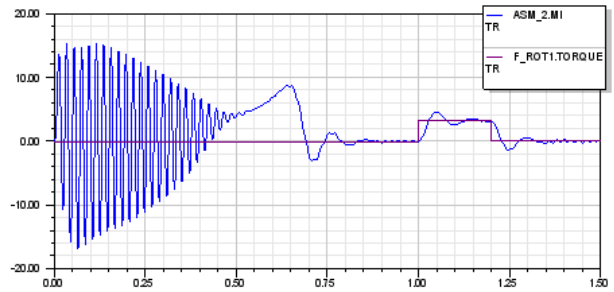


**Figure 3.** Simulation of induction motor: moving torque and load

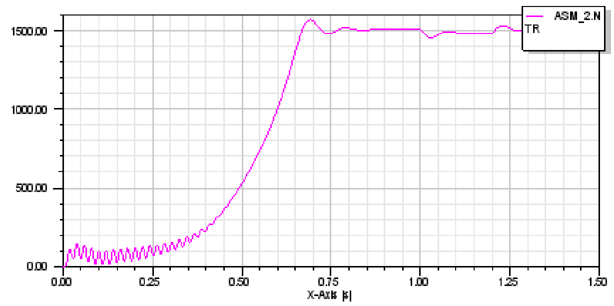


**Figure 4.** Simulation of induction motor: rotor speed

## DC MACHINE LINEAR ELECTRICAL EXCITATION

The model represents a DC machine as a lumped circuit component. By proper connection of armature and excitation circuit, separately excited, series and shunt machines can be modeled. To define the parameter values, enter a numerical value, a variable, or expression in the corresponding field of parameter list [18–20].

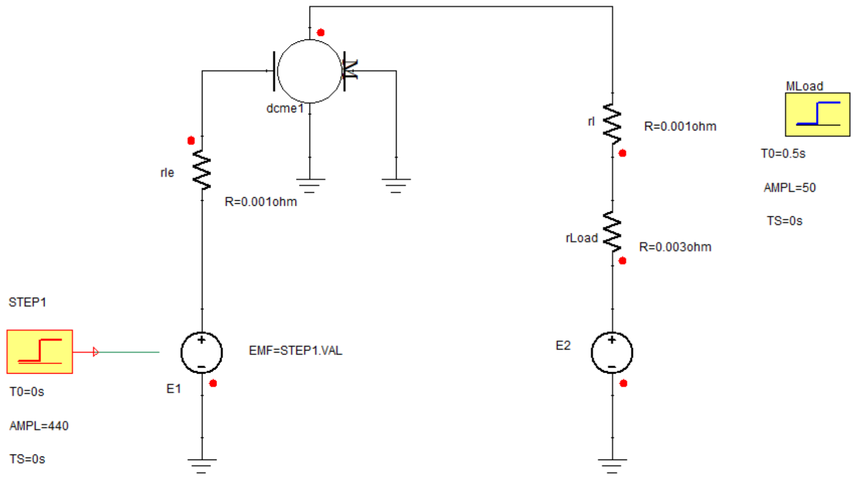


**Figure 5.** Simulation model of DC motor in ANSYS Twin Builder

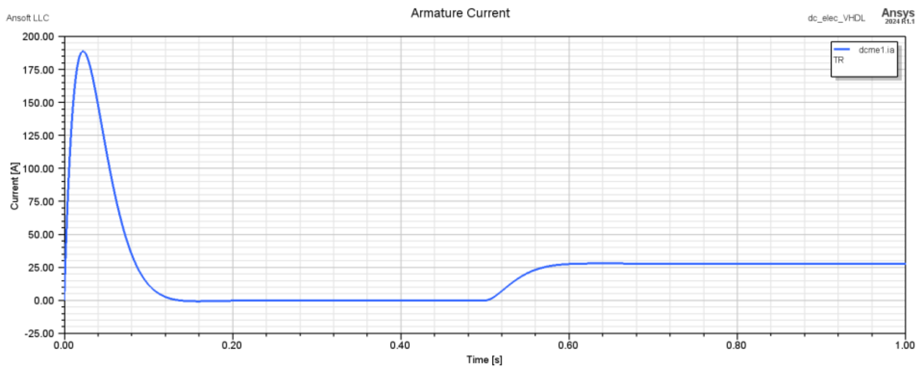


**Figure 6.** Simulation of DC motor: current in armature

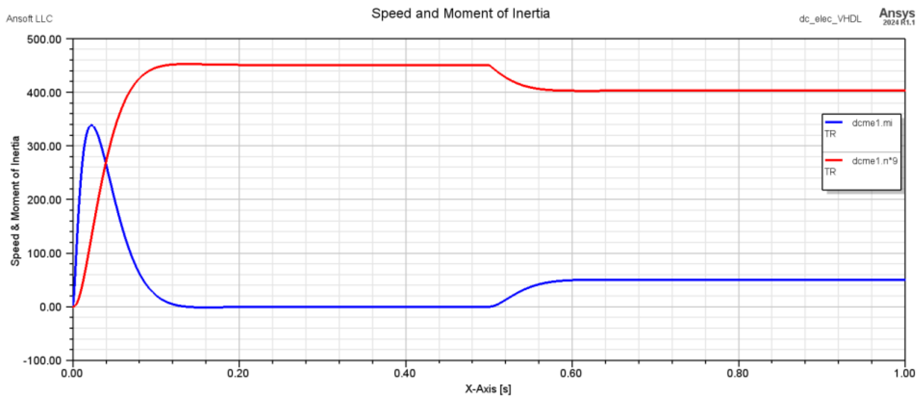


**Figure 7.** Simulation of DC motor: moment of inertia and speed

The equation system is implemented on condition of a linear magnetic circuit. Index a represents the armature circuit quantities, the index e the quantities of excitation circuit.

Model Limits of DC Machine Models:

- the nonlinear magnetic circuit (DC machine with Nonlinear electrical excitation) is able to consider the dependence on excitation flux and inductance caused by the excitation current;
- armature and exciter circuit of the DC machine model are considered to be completely decoupled;
- no consideration of saturation effects in the armature *q*-axis caused by the armature current;
- no consideration of armature reaction on exciting field;
- no consideration of eddy-current and hysteresis loss caused by armature rotation and pulsating-current supply system;
- friction losses (parasitic torques) are not considered in the model; they can be added with the load torque parameter externally.

This example (Fig. 5) demonstrates the setup of a basic DC Electrical Excitation motor with linear excitation and mechanical load. The simulation results are shown in Fig. 6, 7.

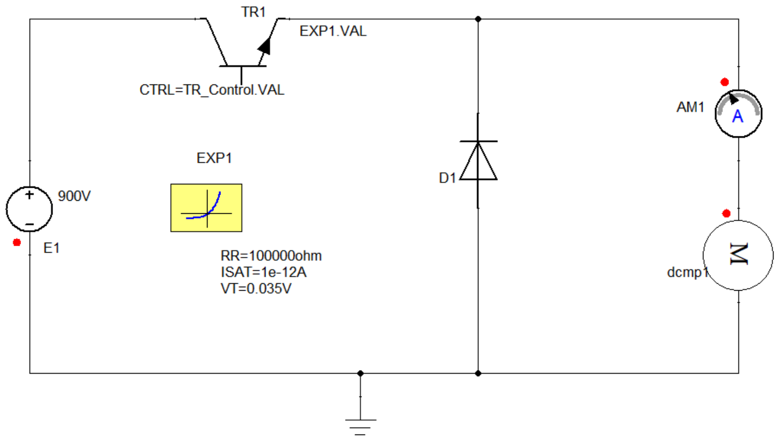


**Figure 8.** Simulation model of DC motor with permanent magnets in ANSYS Twin Builder: power part

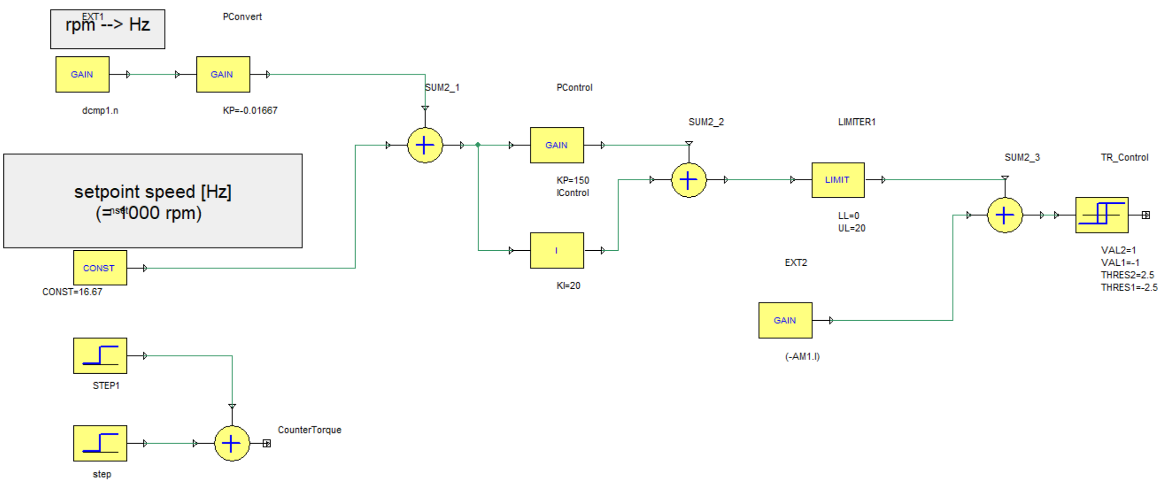


**Figure 9.** Simulation model of DC motor with permanent magnets in ANSYS Twin Builder: control part

## DC MACHINE PERMANENT EXCITATION

The model represents a DC machine with permanent excitation as a lumped circuit component [21–23]. The equation system is implemented on condition of a linear magnetic circuit. Index a represents the armature circuit quantities.

Model Limits of DC Machine Models:

- the nonlinear magnetic circuit (DC machine with Nonlinear electrical excitation) is able to consider the dependence on excitation flux and inductance caused by the excitation current;
- armature and exciter circuit of the DC machine model are considered to be completely decoupled;
- no consideration of saturation effects in the armature $q$-axis caused by the armature current;
- no consideration of armature reaction on exciting field;
- no consideration of eddy-current and hysteresis loss caused by armature rotation and pulsating-current supply system;
- friction losses (parasitic torques) are not considered in the model; they can be added with the load torque parameter externally.

This example (Fig. 8 and Fig. 9) demonstrates the use of a DC Permanent Magnet motor being driven by a switched DC supply. The circuit in Figure 2 shows the supply, switching transistor, and motor hookup. Figure 3 shows the block diagram of the control circuit to sample the motor speed and create the TR_Control signal used to drive the gate of the transistor to provide the proper average voltage to hold the motor at speed. The simulation results are shown in Fig. 10, 11.

## SYNCHRONOUS MACHINE ELECTRICAL EXCITATION WITH DAMPER

The model represents a linear DC field synchronous machine without damper (internal-field) as a lumped circuit component. Depending on the parameter set, the machine can be operated either as a salient or non-salient pole rotor.

The circuit nodes A–B–C are the terminals of star-connected stator winding; the circuit nodes E1–E2 are the terminals of excitation winding [24, 25]. The equation system is implemented in a rotor-fixed (rotor-fixed and also rotor flux-fixed) coordinate system ($d - q$ coordinates).

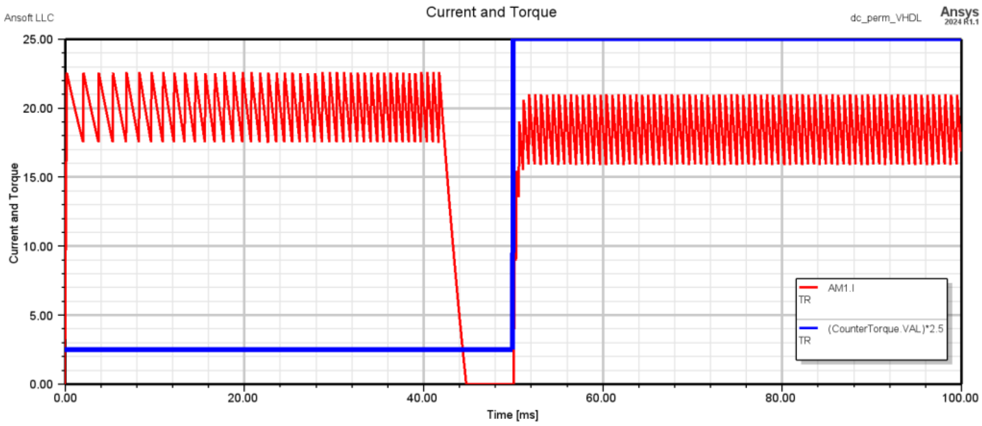


**Figure 10.** Simulation of DC motor with permanent magnets: currents and torque

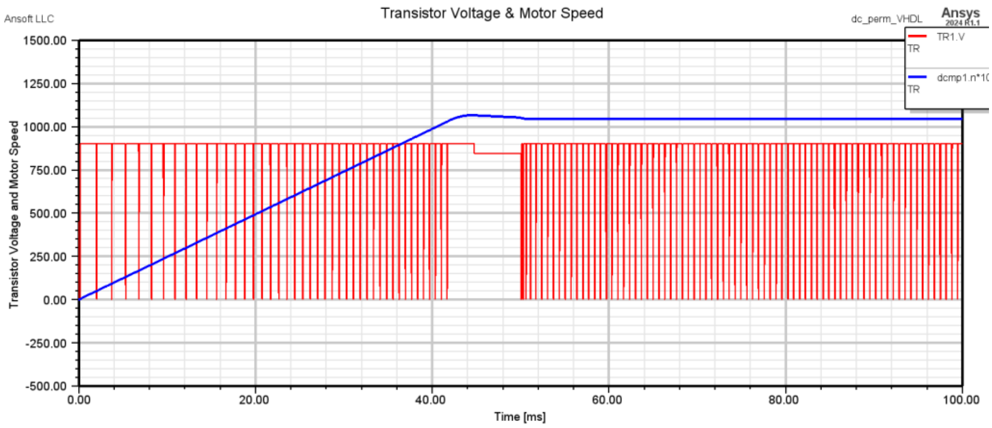


**Figure 11.** Simulation of DC motor with permanent magnets: transistor voltage and motor speed

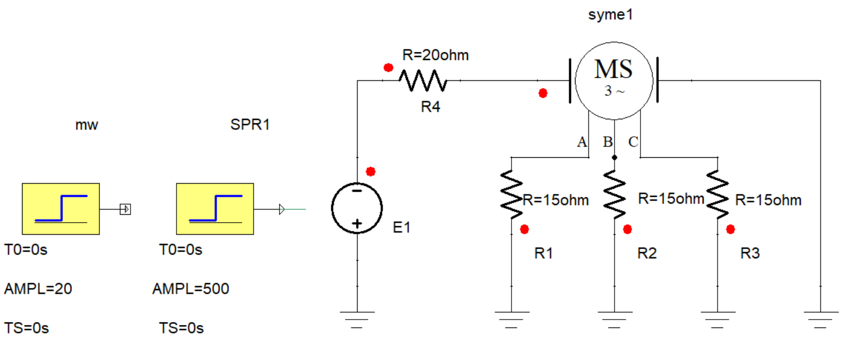


**Figure 12.** Simulation model of synchronous motor in ANSYS Twin Builder

Index *1* represents the stator quantities; the index e the quantities of rotor excitation wingdings. The phase quantities of the real three-phase synchronous machine are indicated with a, *b*, *c*.

If the line-to-line voltage $v_{ab}$, $v_{bc}$, $v_{ac}$ or the line currents $i_a$, $i_b$, $i_c$ of the synchronous machine are of special interest, voltmeters or ammeters can be connected to the synchronous machine.

Model Limits of Synchronous Machine Models:

- -phase symmetrical synchronous machine with internal-field system and star-connected stator winding without neutral node (no zero phase-sequence system);
- linear and iron-loss free magnetic circuit;
- no consideration of skin effects in the windings;
- exclusive consideration of fundamental flux linkage between stator, damper and excitation windings;
- rotor position-independent leakage inductances;
- friction losses (parasitic torques) are not considered in the model; they can be added with the load torque parameter externally.

This example (Fig. 12) demonstrates the use of a Synchronous machine configured as an electrical generator. The simulation results are shown in Fig. 13–16.

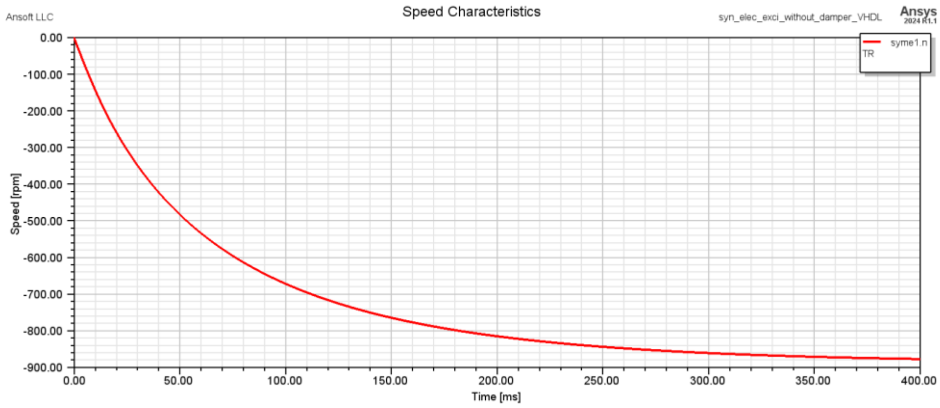


**Figure 13.** Simulation of synchronous motor: rotor speed

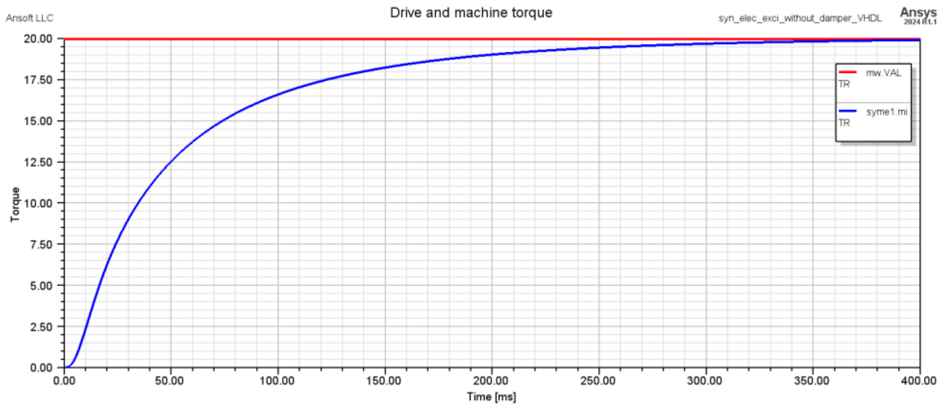


**Figure 14.** Simulation of synchronous motor: drive and motor torque

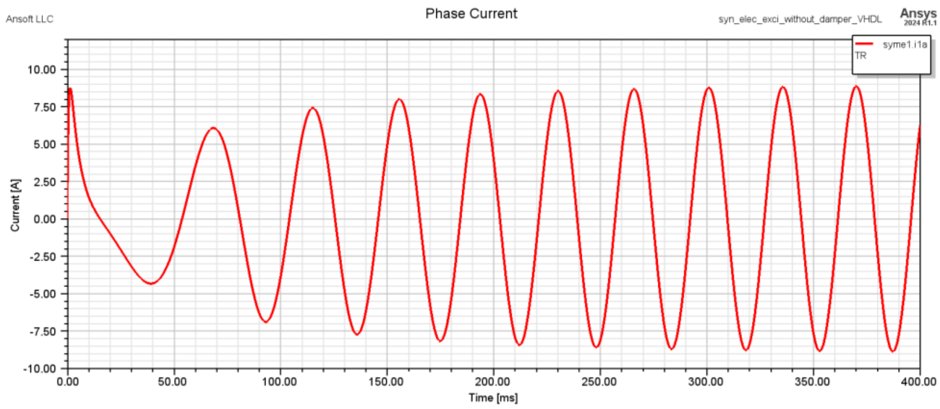


**Figure 15.** Simulation of synchronous motor: phase current

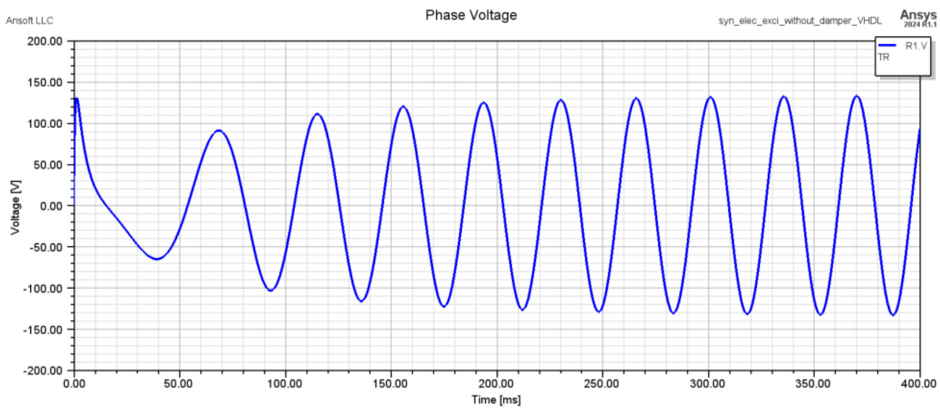


**Figure 16.** Simulation of synchronous motor: phase voltage

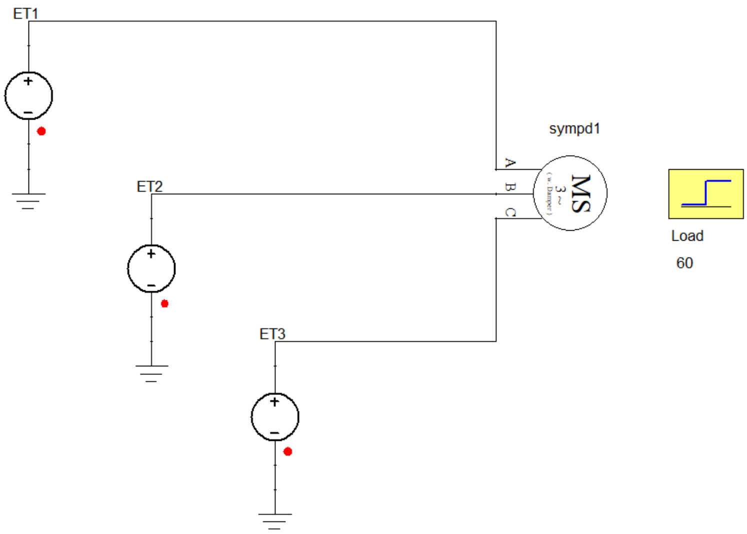


**Figure 17.** Simulation model of synchronous permanent magnet motor in ANSYS Twin Builder

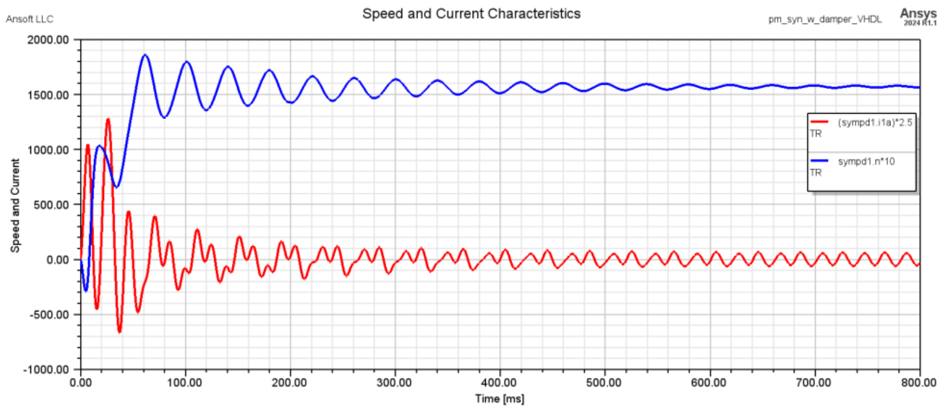


**Figure 18.** Simulation of synchronous permanent magnet motor: speed and phase current

## SYNCHRONOUS MACHINE PERMANENT EXCITATION WITH DAMPER

The model represents a permanent excitation synchronous machine with damper circuit i as a lumped circuit component. The damper circuit is not accessible from outside the machine; the corresponding phase windings are connected at a virtual neutral node. Depending on the parameter set, the machine can be operated either as a salient or non-salient pole rotor. The circuit nodes A–B–C are the terminals of star-connected stator winding [26–30].

In the case of identical parameters for the inductances L1D and L1Q, a synchronous machine with permanent magnet and non-salient pole rotor is modeled. To model a permanent magnet salient-pole machine, the parameters must be different for L1D and L1Q.

The equation system is implemented in a rotor-fixed (rotor-fixed and also rotor flux-fixed) coordinate system ($d-q$ coordinates). Index *1* represents the stator quantities; the index *2* the equivalent quantities of the damper circuit belonged to the rotor. The phase quantities of the real three-phase synchronous machine are indicated with $a$, $b$, $c$.

If the line-to-line voltage $v_{ab}$, $v_{bc}$, $v_{ac}$ or the line currents $i_a$, $i_b$, $i_c$ of the synchronous machine are of special interest, voltmeters or ammeters can be connected to the synchronous machine.

Model Limits of Synchronous Machine Models:

- 3-phase symmetrical synchronous machine with internal-field system and star-connected stator winding without neutral node (no zero phase-sequence system);
- linear and iron-loss free magnetic circuit;
- no consideration of skin effects in the windings;
- exclusive consideration of fundamental flux linkage between stator, damper and excitation windings;
- rotor position-independent leakage inductances;
- friction losses (parasitic torques) are not considered in the model; they can be added with the load torque parameter externally.

This example (Fig. 17) demonstrates the use of a Permanent Magnet Synchronous machine with Damper configured as a motor driving a load. The simulation results are shown in Fig. 18, 19.

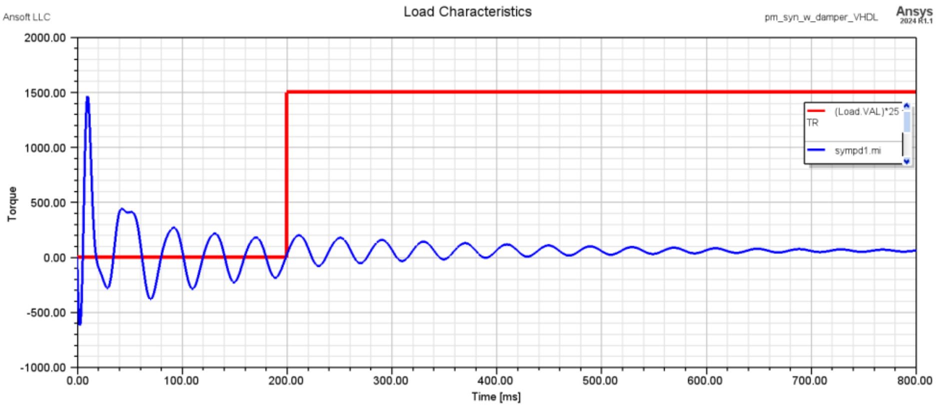


**Figure 19.** Simulation of synchronous permanent magnet motor: moving and load torque

## DISCUSSION

Implementation of digital twins technology bring valuable benefits to electrical machines design, mathematical modelling, predictive analytics and solving coupling projects, that connected to real machines and control systems. Traditional maintenance strategies often rely on scheduled checks, which may result in unnecessary downtime or missed issues between inspections. The digital twin's continuous monitoring and data analysis allow for condition-based maintenance, reducing the likelihood of unexpected failures and optimizing maintenance schedules. By dynamically adjusting operational parameters based on real-time data, digital twins can ensure that induction machines operate at their peak efficiency. This is particularly important in industries where energy consumption is a significant cost factor. With digital twins, engineers can identify inefficiencies caused by wear, load changes, or environmental factors and make real-time adjustments.

The early detection of issues such as rotor bar cracks, insulation breakdowns, or bearing wear allows for timely interventions, reducing the stress on the machine and extending its operational life. By preventing catastrophic failures, digital twins also reduce the need for costly repairs or replacements.

Digital twins facilitate rapid fault identification and diagnosis, as they continuously compare real-time data with ideal performance models. This means that deviations or anomalies can be immediately flagged, helping operators to quickly pinpoint the root cause of a problem. For example, an imbalance in the rotor could be identified through unusual vibration patterns, prompting an investigation before it leads to further damage.

The use of digital twins for electrical machines is expected to expand as sensor technology, machine learning, and data analytics continue to evolve. Future research is likely to focus on improving the accuracy and adaptability of the digital models, particularly under highly dynamic or complex operating conditions. Moreover, the integration of digital twins into Industrial Internet of Things (IIoT) platforms will enable more seamless communication between machines and broader control systems, facilitating a fully connected, autonomous industrial environment.

## CONCLUSIONS

This paper has explored the development of digital twins for several commonly used electrical machines, including the induction machine with a squirrel cage rotor, DC machines with both linear electrical and permanent excitation, and synchronous machines with both electrical excitation and permanent excitation, featuring dampers. By examining the specific characteristics and operational requirements of each machine type, it is evident that digital twin technology provides a valuable tool for improving performance monitoring, optimizing operational parameters, and implementing predictive maintenance strategies. The ability of digital twins to mirror real-time behavior and predict future states allows for enhanced reliability, efficiency, and cost-effectiveness in managing these electrical machines.

Digital twins offer a transformative approach to managing induction machines with squirrel cage rotors. By providing real-time insights into machine health, enhancing predictive maintenance, and optimizing performance, digital twins can significantly reduce operational costs and increase machine reliability, making them a vital tool in modern industrial automation. The implementation of digital twins for these widely used electrical machines holds immense potential for enhancing the reliability, efficiency, and lifecycle management of industrial systems. Future research should focus on refining the accuracy of digital twins, improving sensor technology, and integrating digital twins into broader control systems within the Industrial Internet of Things (IIoT). As the technology evolves, digital twins will become a cornerstone of intelligent maintenance and optimization practices in industries that rely on electrical machines, significantly reducing downtime and improving overall system performance.

## DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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## Цифрові двійники електричних машин різних типів

Владислав Плюгін, Євген Цегельник, Олексій Словіковський

**Анотація.** Зростаючий попит на ефективність, надійність і прогнозне технічне обслуговування в промислових системах викликав значний інтерес до застосування цифрових близнюків електричних машин. Ця стаття має на меті розглянути ключові аспекти щодо створення цифрових двійників для деяких із найбільш часто використовуваних електричних машин, включаючи асинхронну машину з короткозамкненим ротором, машину постійного струму з лінійним електричним збудженням, машину постійного струму з постійними магнітами, синхронну машину з електричним збудженням і синхронну машину з постійними магнітами. Ці машини, критичні в різних галузях промисловості, вимагають точного моделювання та моніторингу в реальному часі для оптимізації їх продуктивності та терміну служби. Кожен тип машини створює унікальні завдання для цифрового двійника, наприклад, точне фіксування електромагнітних взаємодій у роторі з короткозамкненою кліткою або моделювання систем збудження в синхронних машинах і машинах постійного струму. У цій статті досліджуються методології подолання цих проблем, зосереджуючись на зборі даних, математичному моделюванні, які корисні у подальшому в аналізі у реальному часі та прогнозній діагностиці. У статті також висвітлюються переваги технології цифрового близнюка, зокрема підвищена ефективність роботи, скорочення часу простою завдяки прогнозному технічному обслуговуванню та оптимізоване керування за змінних умов навантаження. Крім того, обговорюється інтеграція цифрових близнюків у структурі Інтернету речей (IIoT), що відкриває шлях для більш автономних промислових середовищ. Висновки в цій статті дають важливу інформацію як для дослідників, так і для інженерів, які прагнуть запровадити цифрові двійники в системах електричних машин, сприяючи покращенню промислової автоматизації та управлінню життєвим циклом машини.

**Ключові слова:** цифровий двійник, асинхронний двигун, синхронна машина, постійний магніт, машина постійного струму, моделювання, перехідні процеси

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