

Article

Modeling of Induction Motors and Variable Speed Drives for Multi-Domain System Simulations Using Modelica and the OpenIPSL Library

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Abstract: This paper introduces an innovative method for characterizing, implementing, and validating both three-phase and single-phase induction motor models, accompanied by a variable speed drive model. The primary goal is to investigate interactions between the electrical power grid and other dynamic domains (e.g., thermofluidic) that impact motor/load drive behavior. Our approach involves establishing a mechanical interface based on a physically meaningful equation linking motor torque/speed to the electrical model in the phasor domain. This allows seamless integration of diverse domain subsystems into a unified multi-domain model using Modelica v4.0.0 and the OpenIPSL library v3.0.1, overcoming co-simulation limitations. The proposed model, which requires only one Modelica-compliant tool for simulation, introduces additional dynamics through the mechanical interface, enabling explicit simulation of load disturbances based on constitutive physics. This deepens our understanding of dynamic interactions between the electrical power domain and other subsystems connected through the motor. We detail the modeled components using mathematical equations and textual descriptions, emphasizing the Modelica modeling approach. Simulation examples validate the implementation, demonstrating the multi-domain modeling capabilities of the newly developed components.

Keywords: induction motor models; variable speed drive model; Modelica; OpenIPSL; multi-domain models



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1. Introduction

1.1. Motivation

Electrical motors play a crucial role in converting electrical power into mechanical power for a wide range of applications, from handheld drills that use DC motors to massive industrial loads that use AC motors controlled by variable speed drives (VSDs). Their sizes vary significantly, with power consumption ranging from a few watts to thousands of kilowatts. According to the US Energy Information Administration (EIA), electrical motors collectively represented the largest share of electricity consumption by US manufacturers in 2018, representing approximately 51.6% of the total use of electricity in the industrial sector. Despite the long-standing knowledge and experience in the electrical machine sector, companies such as General Electric (GE) continue to improve motor efficiency and robustness. Notably, GE has recently introduced the world's largest three-phase electrical motor, specifically designed for the liquefied natural gas (LNG) industry [1]. Given the importance of the induction motor in power system design and operation studies [2], power system simulation tools, such as Siemens PTI PSS[®] E [3], Power System Toolbox (PST) [4], Power System Analysis Toolbox (PSAT) [5], PowerWorld [6], and GE PSLF [7], all provide motor models that can simulate the dynamics of a three-phase induction motor in positive

sequence phasor domain representation. The caveat to these induction motor models is that the driven load dynamics are simplified and represented by polynomial functions that are meant to “emulate” the load torque. This means that traditional induction motor modeling is detached from the physical representation of the load itself, and this is due to the modeling philosophy on which conventional power system tools were built. In fact, all physical domains that diverge from the electrical phasor domain representation of the motor are simplified by transfer functions that capture the dynamics of the main time constants of the real processes, efficiency expressions that substitute differential equation modeling, or even fitted polynomials [8]. While this approach is useful for macroscopic studies focused solely on the behavior of the power grid, it is insufficient for understanding more complex interactions driven by the actual dynamics of the loads. An example would be the creation of more substantial efficiencies and services from building-to-grid interactions by leveraging more microscopic control of the load behavior and that of the end user [9].

Over the years, the Western Electric Coordinating Council (WECC) has updated and proposed new load models for dynamic simulation of the power system, including a composite load model that aggregates motors and static loads into one single load model [10,11]. The composite load model can be used to represent residential, commercial, and industrial loads for dynamic studies by adjusting the built-in parameters of the model. Although it is an improvement over previous generations of load models, commercial power system tools are still limited when dealing with multiple domains, e.g., representing the underlying process driving the load using simplified mathematical expressions and not the process’ constitutive physics. In fact, a relevant example of the need to build more detailed motor models becomes clear when studying microgrids where the interaction of power and thermofluid systems exist [12]. Gas turbines, which are typically used in combined heat and power (CHP) plants, generate electricity, but also produce thermal energy, which is used to heat buildings within the microgrid. Electrical water pumps are utilized to transport heated fluid into buildings and also to pump it back to the thermal source (CHP). Thus, to model and study these multi-domain systems and processes, a motor model with its mechanical interface to connect with other domains is necessary. Therefore, in the process of developing motor models that display the mechanical interface, the term multi-domain model refers to the addition of a physically meaningful mechanical interface to the motor that allows it to be coupled to different domains represented by their constitutive physics. With the new addition to the motor model, the user can study the complex inter-domain interactions, creating a more comprehensive environment than traditional power system tools allow.

Instead of using common co-simulation approaches for the coupling of subsystems using different established tools for each specific domain [13], our aim is to integrate the subsystems into one monolithic model simulated in one tool using the Modelica language. In this way, one can avoid several limitations such as the following: (a) numerical stability issues of co-simulation, (b) difficulties in choosing the right co-simulation orchestration algorithm (master), and (c) difficulties in how to define the macro step size for a specific co-simulation, just to name a few [13]. Although the benefit of avoiding co-simulation is attractive, this implies that models not available in the Modelica language or provided as functional mock-up units for model exchange would need to be re-implemented in one of these standards, which naturally implies an investment of time and effort. While the simulation performance of Modelica-compliant tools has been a concern in the past [14], recent developments addressing this issue for large-scale complex models have resulted in major improvements [15], and the case of power systems, these tools are now as competitive as legacy domain-specific tools [16].

This work also implements a variable speed drive (VSD) model, which is not present in traditional power system analysis tools. Although VSDs are typically examined independently of the power grid by experts in power electronics, it is essential to recognize their significance in industrial settings as a means of regulating motor operations. This underscores the need for a suitable model, particularly when aiming to improve efficiency and

services through interactions between buildings and the grid [9]. VSDs enhance motor performance by minimizing the potential for motor damage when starting and stopping, thus extending motor life, consequently decreasing the need for motor maintenance services, and improving energy conservation [17,18].

With this in mind, this article is focused on describing the implementation of the novel multi-domain models and the VSD drive, which were developed using the Modelica modeling language [19] and are compatible with the Open-Instance Power System Library (OpenIPSL) [20]. The Modelica language is an object-oriented multi-domain modeling language used to simulate complex cyber-physical systems [21], which allows for model representation in the form of equations, and seamless creation and connection of components from multiple different domains. OpenIPSL is an open-source Modelica-based library that was developed as an alternative to the standard commercial power system tools in the market.

1.2. Contributions

The current paper proposes the following contributions:

1. The implementation of phasor-based three-phase and single-phase multi-domain electrical motor models.
2. The implementation of a VSD model that allows for simulating the speed control operation over induction motors.
3. The description of a multi-domain model that illustrates the interaction between a thermofluidic system and the electrical grid.

These contributions will be expounded upon in the body of this manuscript, while a summary of each is described next.

In Contribution 1, the proposed models were developed so that they could be used in conventional power system simulations or multi-domain simulations. In the latter, the proposed models are capable of coupling the electrical domain (the motor and a three-phase VSD model for motor control studies) with the mechanical domain (the driven load). While the positive sequence modeling of motors is the de-facto modeling approach in dynamic power system tools, the motor model with an interface to couple with another domain using the Modelica language is novel and allows studying the dynamic interaction between the electrical and other domains.

In Contribution 2, we provide a capability that is neither found nor modeled in standard phasor domain dynamic power system tools. Because the new motor models can be coupled to the VSD model, this also implies that the motor models have frequency-varying stator and rotor impedances, which is also an improvement to the de-facto modeling approaches used by power system tools. Considering the numerous advantages of using the VSD in current induction motor applications, the proposed Modelica-based VSD model is a crucial addition for researchers studying interactions between the power grid and other energy systems.

Finally, in Contribution 3, the proposed two examples illustrate how the developed models allow for multi-domain modeling by including a thermofluidic system that is driven by a pump. In addition, it also displays the ability to couple components from different Modelica libraries into a single model thanks to the motor models developed in this paper.

1.3. Paper Organization

The remainder of this paper is divided into the following sections. Section 3 describes the Modelica modeling rationale used to develop the three- and single-phase induction motor models. Section 4 describes the implementation of the variable speed drive. Section 5 describes the validation process utilized for the motor models with multi-domain interfaces, simulations that test the performance of the motors, and multi-domain application examples. Finally, Section 6 presents the conclusions of this work and outlines future work.

2. Materials and Methods

It is strongly recommended that the reader refers to the actual implementation together with the presentation in this paper. The reader can access and test the models by downloading them from the following GitHub repository: OpenIMDML <https://github.com/ALSETLab/OpenIMDML> (accessed on 16 April 2024), and following the usage instructions described in [22].

Although the simulation results presented here were generated using the Dymola 2023x software [23], the repository tutorial provides instructions on how to run examples using OpenModelica, which is an open-source Modelica-compliant simulation environment [24].

3. Induction Motor Modeling

The industrial sector is the main electricity consumer in the world, consuming roughly half of the total power produced in the world. In countries such as the United States and Canada, of all industrial loads, electrical motors contribute approximately 75% of the consumed power [25]. Electrical motors convert electricity into driving torque, and most electrical motors can be grouped into two categories, namely alternate current (AC) and direct current (DC) motors. As their names imply, AC motors convert alternating voltage and current into mechanical power, while DC motors generate mechanical power out of direct voltage and current. From these two main categories, the AC induction motor is by far the most common and widely used type of electrical motor in residential, commercial, and industrial applications [25]. The induction motor requires a continuously rotating magnetic field in its stator to induce alternating current in the rotor circuit, which consequently induces electromagnetic torque. Of all the possible electrical motors, the induction motor is by far the most widely used type of electrical motor in industrial applications and is the main focus of the motor models developed. With the focal point of developing induction motor models in a multi-domain modeling environment that allows the coupling of multiple physical domains at once [26], the motor models described in this paper were developed to fill this gap.

The motor models described in this paper can be divided into two main categories, “non-multi-domain” (NMD) and “multi-domain”. The term “non-multi-domain” refers to models that represent mechanical loads according to power system modeling practices. Meanwhile, the term “multi-domain” (MD) refers to models with a physically meaningful equation-based interface that couples the motor shaft to a subsystem driven by the motor. Such a subsystem can be represented by a detailed dynamic model of the load, if desired.

- Non-multi-domain (NMD) induction motor models:** The non-multi-domain (NMD) group of models contains both single-phase and three-phase induction motor models. The single-phase induction motor models (single-phase induction motor model and the double-phase induction motor model) were derived from the “classic” Electric Machinery book by Fitzgerald [27], while the three-phase induction motor models (Type I, Type III, Type V, CIM5, and CIM6) were derived from the PSS[®] E and PSAT model manuals [3,8,28]. These NMD models do not include an interface for multi-domain (MD) modeling and, hence, are limited to the load torque polynomial function that is consistent with power system modeling practices. Nevertheless, to expand the features of these models, the implementation reported in this work is such that the impedances of the motor model vary with changing frequencies, i.e., they are frequency-dependent and not constant. Moreover, these models were used as a stepping stone toward the goal of implementing MD models, and since NMD and MD motor models have the electrical part in common with the difference in the mechanical interface, this paper focuses on describing the modeling process adopted to develop the MD models. Although the primary emphasis of this article lies in the development and elucidation of MD motor models, for completeness, Section 5.2 presents the validation results for the NMD CIM5 motor model.

- **Multi-domain (MD) induction motor models:** The multi-domain (MD) group of models contains three-phase, single-phase, and double-phase MD induction motor models. These motor models were developed based on the description of the model in [3,8,28]; they were modified to account for changes in the impedance of the winding based on the change of the terminal voltage frequency and the mechanical interface that allows coupling with mechanical rotation components of the Modelica Standard Library (MSL) [29]. More details are provided in the following sections.

The electrical circuits of the induction motors described above are found in Appendix E. The following subsections detail the models, including the modeling structure of the motors developed. In order to avoid repetitiveness, the authors will exemplify the structure of the Modelica-based motor models through the description of one three-phase motor model, one single-phase, and a dual-phase motor.

3.1. Three-Phase Induction Motor Model

One of the key features of the Modelica modeling language is its object-oriented nature, which allows the extension of the behavior and properties of an existing class [19,21]. In Modelica (see the Modelica language specification: <https://specification.modelica.org/> accessed on 16 April 2024). Each component of a model is presented as a class, and by using inheritance, a partial (the typewriter font is used to denote Modelica code and Modelica component names) class provides a base class from which a new class/model can be extended. The proposed three-phase induction motor models, whether multi-domain or not, have their own base class model. The following subsections are meant to explain the logic behind the base class and the extended model structure and elucidate the common characteristics between different induction motor models.

3.1.1. Base Class for Multi-Domain and Non-Multi-Domain Models

The NMD three-phase induction motor base class, named *BaseNonMultiDomainThreePhase* (the *italic* font is used to denote the names of the models that are being discussed), defines a common structure for all three-phase motor models, i.e., the basic equations that are ubiquitous to all three-phase NMD motor models. Similarly, the *BaseMultiDomainThreePhase* base model defines the common structure that is present in the developed MD three-phase motor models. Figure 1 depicts both the NMD and MD base classes in their “Icon” view (models in Modelica have multiple views or layers. The “Icon” view provides a user-facing graphical representation, the “Diagram” view is meant to graphically compose system models using multiple components, the “Text” view is where a component’s equations are defined, and the “Documentation” view provides information about the model. See the Modelica language specification: <https://specification.modelica.org/> accessed on 16 April 2024).

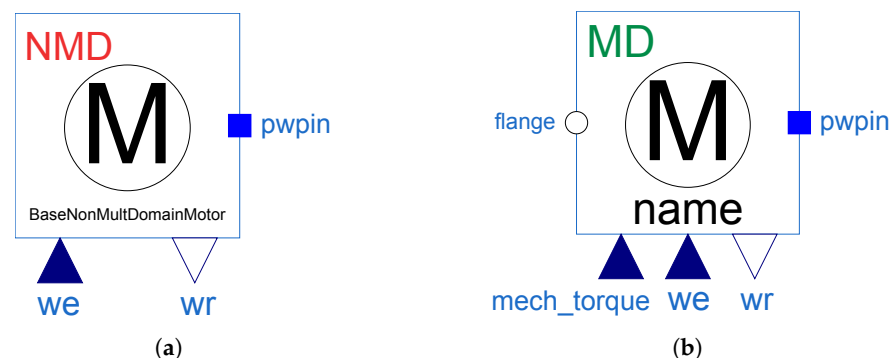


Figure 1. Icon view of the (a) non-multi-domain base class model; (b) multi-domain base class model.

Both base classes provide visual cues that help understand their modeling purposes; in particular, the red NMD acronym in the top corner of the model stands for non-multi-domain, and the green MD acronym stands for multi-domain. More importantly, the NMD

motor in Figure 1a has one physical (acasual) connector (pwpin) and two casual connectors (w_e , w_r), where w_e is a RealInput connector that specifies the desired electrical speed and w_r is a RealOutput connector that provides the mechanical rotor speed. Meanwhile, the MD motor in Figure 1b has the same acasual and casual connectors, in addition to an *acasual* connector (flange) and a casual connector (mech_torque), which are further explained below. The connector pwpin is an *acasual* connector specific to OpenIPSL, which is ubiquitous to all of the electrical component models in the library. It follows the grammar of several MSL subdomain packages, where the connector has potential and flow variables. In the case of OpenIPSL, the real and imaginary parts of the current that flow through the components arise from the real and imaginary parts of the voltage phasor values in the nodes of the system, defined by the buses [30].

While Figure 1 shows the icon view of the base class model, in Figure 2, the diagram view shows the structure of the base class model for the multi-domain version of the three-phase induction motor models.

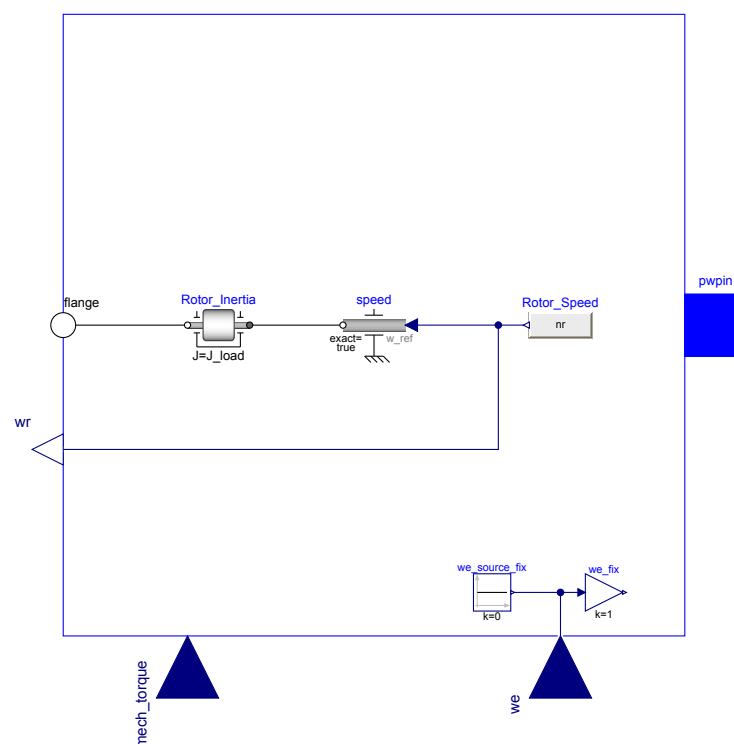


Figure 2. Diagram view of the multi-domain base class model for three-phase induction motors.

The “Icon” view is the graphical representation of a model, and when dragged into a sub-system or system model, the user will interact with it (e.g., providing parameters). Meanwhile, the “Diagram” view shows how the model is composed of several other sub-components that are being used in the creation of the motor base class. For instance, in order for the model to interface with rotational components from the Modelica Standard Library, the rotor speed n_r (which is calculated in the equation section of the base model within the “Text” view of the base component) is used as a reference value to the speed component, which forces the flange to rotate at the specified speed, converting the rotor speed n_r into its equivalent torque and angle. For more information on the rotational components from the MSL and their modeling attributes, refer to [29].

Traditional power system stability software does not model motors as frequency and voltage-controlled equipment. However, in this work, both the NMD and MD models described in the work represent motor reactances based on the terminal bus frequency. The input connector w_e allows for adjusting the synchronous speed of the NMD motor model in rad/s , while the output connector w_r is the resulting rotor speed in rad/s . In the case of

traditional phasor domain power system tools, the impedance of all the components is tied to the system frequency (including the impedances in the motor), thus limiting motor simulations to grid-tied only. In contrast, the proposed motor models are more versatile, allowing for dynamic grid-tied motor simulation, grid-tied starting motor simulation, soft start motor simulation, and VSD-controlled motor simulation. All reactances of the rotor, stator, and magnetization windings vary with the frequency of the input voltage signal through the ratio $\frac{weX}{w_b}$, where X represents reactances of the motor model and w_b is the nominal synchronous speed of the electrical grid. For instance, the set of frequency-varying reactances of Motor Type III is defined as follows:

$$\begin{aligned} X_m^{cont} &= \left(\frac{we}{w_b} \right) X_m^{nom} \\ X_s^{cont} &= \left(\frac{we}{w_b} \right) X_s^{nom} \\ X_r^{cont} &= \left(\frac{we}{w_b} \right) X_r^{nom} \end{aligned}$$

where X_m^{cont} , X_s^{cont} , and X_r^{cont} are the frequency-varying magnetization, stator, and rotor reactances; X_m^{nom} , X_s^{nom} , and X_r^{nom} are the nominal frequency magnetization, stator, and rotor reactance.

Exclusive to the MD model, its base class contains a `flange` connector port and the `mech_torque` input port. The `acasual flange` connector has a potential variable, which is the absolute rotation angle, and a flow variable, which is the cut torque. It is because of the `flange` connector that the model can be interfaced with rotational mechanical components from the MSL library [29], allowing the motor model to be coupled to any components with a matching `flange` connector. The load torque in the MD model is specified through `mech_torque`, which originates from a torque sensor that measures the torque in the MD load. The set of equations that define the base class model is shown in Listing 1.

Listing 1. Set of equations for the non-multi-domain and multi-domain motor base class in Modelica.

```
(1) - Synchronous speed based on controllable boolean parameter
w_sync = (if Ctrl == true then we else w_b);

(2) - Network Interface Equations
[Vr; Vi] = [p.vr; p.vi];
[Ir; Ii] = (1/CoB)*[p.ir; p.ii];
Imag = sqrt(Ir^2+Ii^2);
v = sqrt(p.vr^2+p.vi^2);
anglev = atan2(p.vi, p.vr);

(3) - Active & Reactive Power Consumption on system base
P = p.vr*p.ir+p.vi*p.ii;
Q = (-p.vr*p.ii)+p.vi*p.ir;

(4) - Active & Reactive Power Consumption on machine base
P_motor = P/CoB;
Q_motor = Q/CoB;

(5) - Rotor speed equation
ns = w_sync/N;
nr = (1-s)*ns;

(6) - Conversion from SI torque to p.u. torque
Tmech_pu_sys = mech_torque/T_b;
Tmech_pu_motor = Tmech_pu_sys/CoB;

(7) - Torque System base
T_b = S_b/w_b;
```

Listing 1 is the set of common equations from the *BaseNonMultiDomainThreePhase* and *BaseMultiDomainThreePhase* base models, and are divided into seven different sections.

- **Equation (1):** Presents one equation that corresponds to the synchronous speed equation that enables all three-phase induction motor models from the library to be controllable. `Ctrl` is a user-defined Boolean parameter that, if chosen to be true,

enables the motor model to connect to a motor control component, such as the VSD, and if deemed false, disables the controllable aspect of the motor model.

- **Equation (2):** Defines the algebraic equations that are necessary for interfacing the motor model with power grid components through the `pwpin` connector that is instantiated as `p` with variables `p.vr`, `p.vi`, `p.ir`, and `p.ii` corresponding to the real and imaginary parts of the voltage and current at `p`.
- **Equation (3):** Describes two algebraic equations that correspond to the active (P) and reactive power (Q) consumption of the motor model for the system's apparent power base, linking the voltage and current variables from the `pwpin` connector.
- **Equation (4):** Describes two algebraic equations for motor active and reactive power consumption, based on the motor's apparent power base. Here, `CoB` is the motor change of the base from the system power base to the motor power base.
- **Equation (5):** Defines the magnetic field synchronous speed `ns` and the effective rotor speed `nr`, respectively. The parameter `N` is the number of pairs of poles of the motor and `s` is the motor slip variable.
- **Equation (6):** Specifies the mechanical torque expressed in per unit [*p.u.*] for the system base and the motor base. The variable `T_b` is the torque system base; it is used to convert mechanical torque from the Newton meter [*N.m*] to [*p.u.*].
- **Equation (7):** Defines a system base torque value for unit conversion.

The next subsection explains how the base model is extended to create the three-phase induction MD and NMD motor models.

3.1.2. Creating Multi-Domain and Non-Multi-Domain Motor Models with Inheritance

This subsection describes the implementation of the extended MD model of the three-phase motor that applies to all its variants (see Appendix E, Figures A1a–d). In order to avoid repetitiveness, this subsection will only describe the model extension of the motor model Type III MD model. The modeling procedures for the other developed three-phase induction motor models are similar to the one described in this section and, thus, for the sake of brevity, they will be omitted.

As mentioned in the previous subsection, given the object-oriented nature of the Modelica modeling language, the creation of base classes allows us to define all common variables, parameters, equations, etc., which can be inherited in a new model class. As a result, the NMD AND ND motor models share the same icons in Figure 1 and equations as in Listing 1. Meanwhile, Listing 2 contains the set of complementary equations that uniquely defines the Type III induction motor model, divided into five sections.

Listing 2. Modelica set of equations for the three-phase multi-domain induction motor model type III.

```
(8) - Rotor impedance based on controllable model
X0 = if Ctrl == false then Xs+Xm else (we_fix.y/w_b)*(Xs+Xm);
Xp = if Ctrl == false then Xs+X1*Xm/(X1+Xm) else we_fix.y*(Xs+X1*Xm/(X1+Xm))/w_b;
Tp0 = if Ctrl == false then (X1+Xm)/(w_b*R1) else (we_fix.y/w_b)*(X1+Xm)/(w_b*R1);

(9) - The real and imaginary current relationship
Vr = epr+Rs*Ir-Xp*Ii;
Vi = epm+Rs*Ii+Xp*Ir;

(10) - Electromagnetic differential equations
der(epr) = w_sync*s*epm-(epr+(X0-Xp)*Ii)/Tp0;
der(epm) = (-w_sync*s*epr)-(epm-(X0-Xp)*Ir)/Tp0;

(11) - Mechanical Slip Equation
der(s) = (Tmech_pu_motor-Te_motor)/(2*H);

(12) - Electromagnetic torque equation in system and machine base
Te_sys = Te_motor*CoB;
Te_motor = if Ctrl == false then (epr*Ir+epm*Ii) else (epr*Ir+epm*Ii)/(we_fix.y/w_b);
```

- **Equation (8):** Defines two distinct induction motor reactance calculations, `X0` and `Xp`, as well as an open-circuit time constant, `Tp0`, which are used to determine the real and

imaginary components of the consumed current in Equation Set (9) and the change in real and imaginary voltages behind the stator resistance in Equation (10).

- **Equation (9):** Defines two equations and two unknowns, namely I_r and I_i . The unknown variables are the real and imaginary parts of the consumed motor current, defining the current flow parameters from the `pwpin` connector. It is important to note that V_r and V_i (real and imaginary components of the motor terminal voltage) are potential parameters and are thus known at the initialization step of the simulation. The same can be said for the direct transient magnetization voltage `epr` and quadrature transient magnetization voltage `epm`.
- **Equation (10):** Describes two differential equations for the direct transient magnetization voltage `epr` and quadrature transient magnetization voltage `epm`.
- **Equation (11):** Describes the slip's differential equation, representing the rate of change in the rotor speed as the motor drives a mechanical load. The slip is defined as the ratio between the mechanical and electromagnetic torque difference divided by double the motor's inertia constant.
- **Equation (12):** Defines the electromagnetic torque equation in both the system and machine bases.

3.2. All-in-One Multi-Domain and Non-Multi-Domain Motor Model

In order to encompass all types of three-phase induction motor model types (in Appendix E, see Figure A1a–d for a circuit diagram of the included models) into a single component, two models were developed, namely *MultiDomainMotor* and *NonMultiDomainMotor*. Both encompass one replaceable base class component, either NMD or MD. In Modelica, the `replaceable` keyword is used to designate components in a model whose type can be changed or redeclared, making the model reconfigurable [31].

The use of `replaceable` and `redeclared` allowed us to fully exploit the features of the object-oriented modeling language in Modelica to make the use of all variants of the model more accessible to the user. The user can, through one component only, choose which three-phase motor model type to utilize in the system's simulation model, and whether or not to enable the multi-domain features. This makes it easier to use all available models from a user's perspective, in addition to allowing the user to quickly modify the fidelity of the motor model without the need to change the system model.

The icon view of the *MultiDomainMotor* and *NonMultiDomainMotor* components are similar to the motor icon in Figure 1, differentiating itself with a written "ALL-IN-ONE" text in the icon. Figure 3 shows the parameter selection screen of the *MultiDomainMotor* motor model. The model contains four parameter groups:

- **Power flow data:** Parameter section that defines the initialization values for the dynamic simulation. It is worth mentioning that it does not make sense to enable the user to input values to all parameters because the model is MD. Being MD, the initialization of the model is based on the mechanical model and not on solving a power flow [32]. Therefore, only the parameter `M_b` is enabled, allowing the user to change the value of the motor base power, while the rest are disabled and have a gray fill, indicating that they do not need to be provided to the user.
- **Motor setup:** Parameter section that allows the user to select whether the motor is controllable and whether or not the motor will undergo startup. If `Ctrl` is true, then the motor can be controlled via an output signal that is fed to the `we` real input from Figure 1. If `Ctrl` is false, the motor is non-controllable, meaning that the motor's impedance calculations are based on the nominal synchronous speed value defined inside the model. The parameter `Sup` defines the initial slip, when true, the motor rotor starts from the halt position, and false starts from the steady state.
- **Machine parameters:** Parameter section where the user defines values for parameters that are ubiquitous to all motor models, which are the number of pairs of poles (N) and the rotor inertia (H).

- Motor selection:** Parameter section where the user defines the motor model for simulation. The drop-down item allows the user to choose between different models (*MotorTypeI*, *MotorTypeIII*, *MotorTypeV*, *CIM5*, and *CIM6*). The icon to the right of the drop-down option is the 'Edit' option, where the user can manually type the values of the parameters of the chosen induction motor model. For an example of a *MotorTypeIII* parametrization, refer to Appendix C.

Figure 3. All-in-one *MultiDomainMotor* parameter selection screen.

The same model structure is present in the *NonMultiDomainMotor*, differentiating itself from the *MultiDomainMotor* by the lack of a flange connector; therefore, due to its modeling similarity, the explanation of the *NonMultiDomainMotor* model is omitted.

3.3. Single-Phase and Dual-Phase Induction Motor

Similar to how the MD and NMD three-phase induction motor models were developed, the single-phase induction motor (SPIM) and the dual-phase induction motor (DPIM) have a base class that allows for inheritance. One peculiarity of the SPIM is that due to the physical placement of the main stator poles, the resulting magnetic field pulsates instead of rotating, which is the case for the three-phase induction motor [33]. The consequence of having a pulsating magnetic field is that the motor will not rotate without an initial external torque applied to the rotor. Therefore, single-phase motors in real life include an auxiliary circuit that is switched on during the motor start process and is switched off once the motor reaches a user-defined rotational speed [27]. Due to this fact, single-phase motors can be modeled in two distinct ways: (a) steady-state operation, where the motor is assumed to be in a steady state and the startup process is neglected, and (b) full modeling of the main and auxiliary circuits, leading to the ability to simulate both startup and steady-state conditions. In this paper, when using the term “single-phase” motor models, the authors describe the steady-state representation of the motor, while the term “dual-phase” motor simply refers to the motor that can simulate both startup and steady-state operations. Because of the more complex circuit representation in the dual-phase motor model and because it can represent both steady-state and startup circuitry, the main focus in the following sections is to describe the DPIM motor model in the MD form.

3.3.1. Base Class for Multi-Domain and Non-Multi-Domain Models

The non-multi-domain and multi-domain base class applies to both SPIM and DPIM models, *BaseNonMultiDomainSinglePhase* and *BaseMultiDomainSinglePhase*, respectively, as shown in Figure 4.

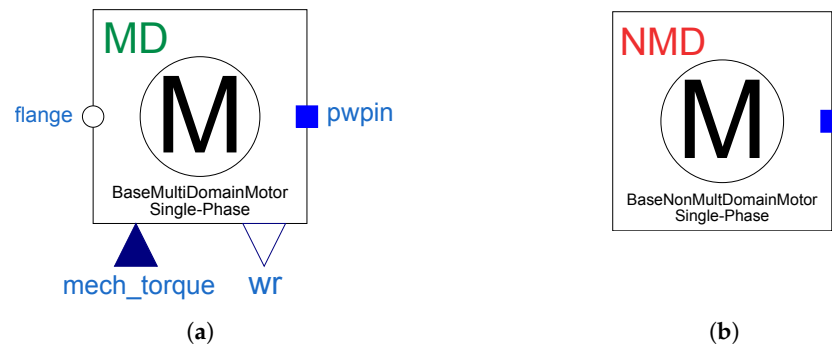


Figure 4. Icon view of the (a) non-multi-domain base class model; (b) multi-domain base class model.

The base class model for the SPIM and DPIM models, either MD or not, is very different from the structure shown for the base class of the three-phase induction motors. This is because the SPIM and DPIM induction motors have very few variables in common and, therefore, models derived from each base class will have different parameters and variables. The NMD base model is mainly comprised of power flow initialization parameters; therefore, all specific parameters and variables that describe each different model are expressed in the (derived) extended model. Figure 5 displays the diagram view of the MD base class model of the SPIM and DPIM models.

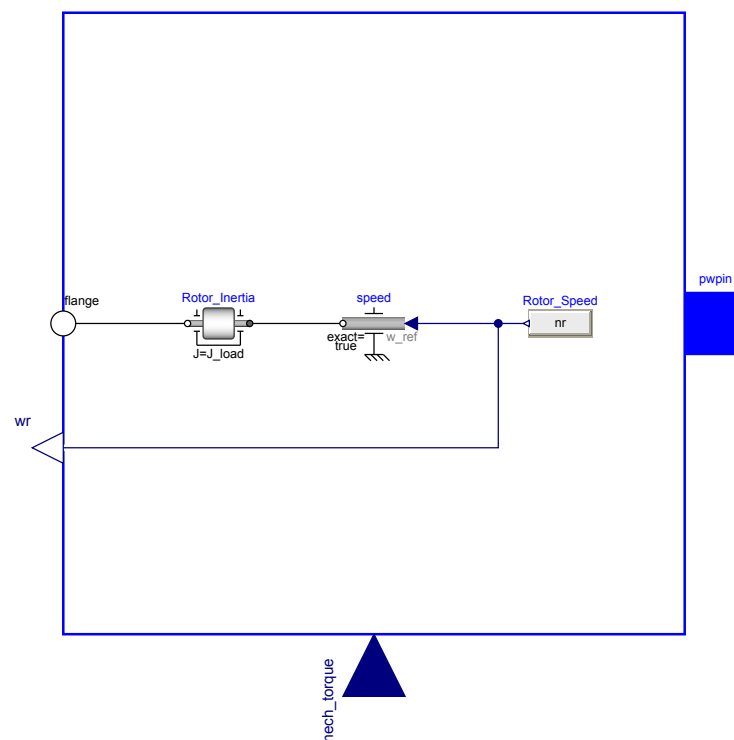


Figure 5. Diagram view of the multi-domain base class model for single-phase and dual-phase induction motors.

The difference between this class and the base class depicted in Figure 2 is the absence of the *w_e*, *RealInput* connector, and its aggregate components. The reason is that small machinery using these types of motors typically does not have variable speed drives connected to them, as they are generally used in applications requiring constant rotating

speeds. The equation section of the MD base class model for the single-phase and dual-phase motors is shown below.

It is not surprising that Equations (1)–(3) from Listing 3 are identical to Equations (5)–(7) from Listing 1 since the interface follows the same structure on both models. The reader is directed to Section 3.1.1 for an explanation of the equation.

Listing 3. Modelica set of equations for the multi-domain single-phase and double-phase base class model.

```
(1) - Rotor speed equation
ns = w_b;
nr = (1-s)*ns;

(2) - Conversion from SI torque to p.u. torque
Tmech_pu_sys = mech_torque/T_b;
Tmech_pu_motor = Tmech_pu_sys/CoB;

(3) - Torque System base
T_b = S_b/w_b;
```

3.3.2. Creating Multi-Domain and Non-Multi-Domain Motor Models with Inheritance

The multi-domain DPIM extended motor model was developed to represent the startup and steady-state dynamics of the single-phase motor; to do so, the model required representation of both the main and auxiliary electrical winding circuits [27]. Due to the specific utility of the auxiliary winding, which involves generating a rotating electromagnetic torque during startup in single-phase motors, several different auxiliary winding circuit implementations are found in real-life single-phase motors. This paper will focus on describing two motor configurations, namely split-phase and capacitor-start single-phase motors (see Figure A1f,g in Appendix E). Split-phase motors have a modest starting torque and are used for applications that do not require high starting torques (fans, blowers, and centrifugal pumps). Meanwhile, capacitor-starter motors are more expensive, as they are implemented with an extra capacitor in the auxiliary winding for high starting torque capability (typically found in compressors, pumps, and air conditioners) [34]. Once the auxiliary winding circuit is disconnected, the single-phase motor operates under the magnetic field generated by the main winding, which is how the SPIM motor is modeled in the literature. For that reason, because of DPIM's dual modeling capabilities, this section will focus on describing the Modelica equations that constitute the DPIM model. Listing 4 contains the set of complementary equations that uniquely defines the DPIM motor model, divided into twelve sections—three that are presented in Listing 3 and attributed by inheritance, and the remainder presented in Listing 4.

Listing 4. Modelica set of equations for the dual-phase multi-domain induction motor model.

```
(4) - Reactance of the Capacitor, Main and Aux Winding
Xc = 1/(w_b*Cc);
Xmain = w_b*Lmain;
Xaux = w_b*Laux;

(5) - Main and Aux Flux Linkage Coefficient Calculations
Kplus = (s*w_b)/(2*(Rr + j*s*w_b*Lr));
Kminus = (2 - s)*w_b/(2*(Rr + j*(2 - s)*w_b*Lr));

(6) - Main and Aux Flux Linkage Calculations
Lambda_main = if s > switch_open_speed then (Lmain - j*Lmainr^2*(Kplus + Kminus))*Imain +
    Lmainr*Lauxr*(Kplus - Kminus)*Iaux else (Lmain - j*Lmainr^2*(Kplus + Kminus))*Imain;
Lambda_aux = if s > switch_open_speed then - Lmainr*Lauxr*(Kplus - Kminus)*Imain + (Laux -
    j*Lauxr^2*(Kplus + Kminus))*Iaux else 0*j;

(7) - Main and Aux Winding Voltage
Vmain = V_b*(p.vr + j*p.vi);
Vaux = if sm > switch_open_speed then Vmain else 0*j;

(8) - Main and Aux Winding Current
Imain = (Vmain - j*w_b*Lambda_main)/Rmain;
if sm > switch_open_speed and init == 1 then
```

```

Vaux = Iaux*Raux + j*w_b*Lambda_aux;
elseif sm > switch_open_speed and init == 2 then
Vaux = Iaux*Raux + j*w_b*Lambda_aux - j*Iaux/(w_b*Cc);
else
Iaux = 0*j;
end if;

(9) - Conversion of calculated current to OpenIPSL connector current
p.ir = real(Imain + Iaux)/I_b;
p.ii = imag(Imain + Iaux)/I_b;

(10) - Active and Reactive Power Calculation
P = p.vr*p.ir + p.vi*p.ii;
Q = (-p.vr*p.ii) + p.vi*p.ir;

(11) - Electromagnetic Torque Calculation
Te_pre = (Lmainr^2*Imain*conj(Imain) + Lauxr^2*Iaux*conj(Iaux))*conj(Kplus - Kminus) +
j*Lmainr*Lauxr*(conj(Imain)*Iaux - Imain*conj(Iaux))*conj(Kplus + Kminus);
Te = (N/T_bm)*real(Te_pre);

(12) - Mechanical Slip Equation
der(s) = (Tmech_pu_motor - Te)/(2*H);

```

- **Equation (4):** Defines the reactance of the capacitor (X_c), the reactance of the main winding (X_{main}), and the reactance of the auxiliary winding (X_{aux}). The parameter (C_c) is the auxiliary winding capacitance, the (L_{main}) is the main winding inductance, and (L_{aux}) is the auxiliary winding inductance.
- **Equation (5):** K_{plus} and K_{minus} are coefficients that are used during the calculation of the electromagnetic torque.
- **Equation (6):** Describes the flux linkage of the main (Λ_{main}) and auxiliary (Λ_{aux}) winding. Both flux linkage equations have if statements that are related to the auxiliary winding switching. During the startup process, the main winding circuit is parallel with the auxiliary winding circuit and the resulting flux linkage is different from when the main winding is the only circuit generating flux.
- **Equation (7):** Defines the main and auxiliary winding complex voltage values. Once more, (V_{aux}), which is the auxiliary winding terminal voltage, has a different value during the startup and steady-state operations, determined by an if statement.
- **Equation (8):** Defines the current through the main winding (I_{main}) and the auxiliary winding (I_{aux}). The reader will notice that there are two distinct equations for determining the (I_{aux}) value, related to the auxiliary winding configuration (decided as a parameter ($init$) that the user can choose).
- **Equation (9):** Conversion of real and imaginary currents from ampere to per unit to comply with the p_{wpin} OpenIPSL connector, instantiated as p .
- **Equation (10):** Active (P) and reactive (Q) power calculation on the system base S_b .
- **Equation (11):** Calculation of the electromagnetic torque (T_e) generated by the DPIM motor model.
- **Equation (12):** Describes the slip differential equation, representing the rate of change in the rotor speed as the motor drives a mechanical load. The slip is defined as the ratio between the mechanical and electromagnetic torque difference divided by double the motor's inertia constant.

4. Variable Speed Drive Modeling

Conventional three-phase induction motors connected directly to the grid, once in a steady-state condition, operate at a single speed defined by the frequency of the grid's voltage. However, in many industrial applications, one must control the motor's speed and torque in order to fulfill a specific task, or with the overall goal of improving productivity and energy savings in pumps, fans, compressors, etc. Thus, induction motors are controlled via variable speed drives (VSDs), which are power electronic converters that enable the control of the motor's terminal voltage magnitude or frequency. The power electronic interface of a standard VSD is shown in Figure 6.

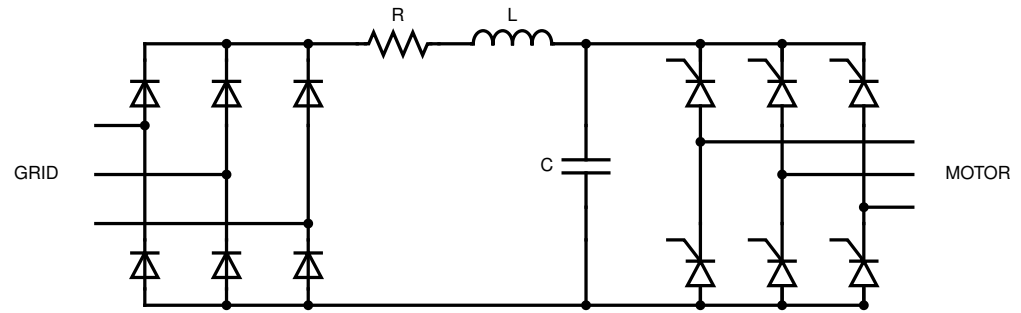


Figure 6. Typical VSD three-phase power electronic circuit.

The power electronic circuit of a VSD is typically built using a rectifier, a DC link circuit, an inverter, and its controller. The diode bridge (on the grid side) is composed of passive components, i.e., there is no means of controlling the diodes. However, the controllable side of the power electronic interface is on the thyristor bridge (on the motor side), where the frequency and angle of the AC motor voltage side are controlled through the switching of the thyristors. To reduce the simulation time required to represent the switching operations from the VSD power electronics interface, the authors chose to model the VSD power electronic interface in its “averaged” form. This representation provides an approximate “average response” that allows for much faster run times and avoids the problem of creating state events during simulation. Since the average model does not account for the switching component, the rectifier and inverter can be represented as shown in Figure 7.

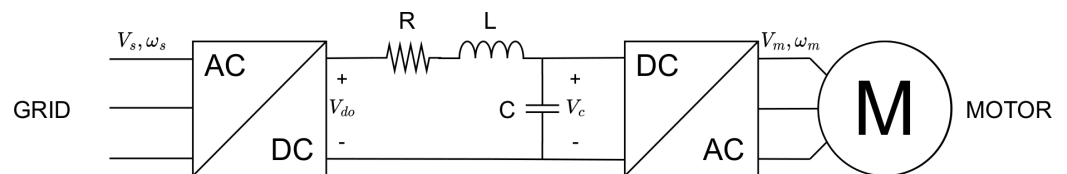


Figure 7. Typical VSD three-phase average power electronic circuit.

The average rectified DC voltage V_{do} is defined as follows:

$$V_{do} = \frac{3\sqrt{2}}{\pi} V_s \cos \varphi \quad (1)$$

where V_s is the magnitude of the AC phasor voltage of the grid and φ is the angle of the diode rectifier ($\varphi = 0$). The capacitor in the DC link circuit is responsible for holding a constant DC voltage, V_c , during the steady state. The magnitude of the AC phasor voltage, V_m , on the motor side, is modeled as a function of V_c and a pulse width modulation (PWM) index, m . The phasor voltage on the motor side is as follows:

$$V_m = \frac{\sqrt{3}}{2\sqrt{2}} m V_c \quad (2)$$

The motor voltage angle is chosen to be zero as it is the new reference to the motor and its magnitude depends on V_c , the capacitor’s voltage, and the PWM modulation index.

The controllable parameter on the inverter side is the PWM index, which characterizes the amplitude modulation of the motor terminal voltage. Together with the voltage magnitude, the VSD controls the frequency of the motor terminal voltage, which automatically impacts the synchronous speed of the rotating magnetic field in the three-phase induction motor. The VSD control strategy that is the most common in industrial applications is scalar control, specifically the volts/hertz control. By increasing the motor terminal voltage and frequency at a constant ratio, it is possible to maintain an almost constant magnetic flux density in the motor air gap. Maintaining constant magnetic flux ensures constant

electromagnetic torque in the motor, which is a desirable outcome. The volts/hertz logic diagram is shown in Figure 8.

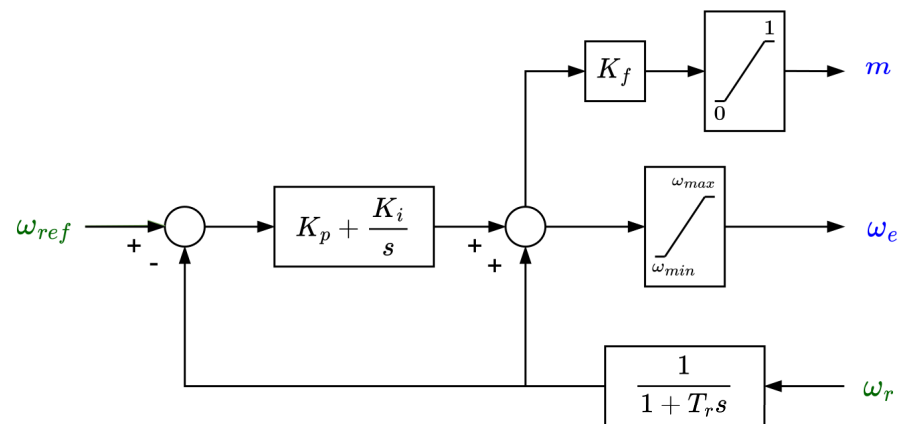


Figure 8. Closed-loop volts/hertz control diagram.

The controller inputs are the green variables ω_r (rotor speed) and ω_{ref} (synchronous reference speed), while the controller outputs are the blue variables m (PWM modulation index) and ω_e (synchronous speed). The m output variable is limited in the range of $0 < m < 1$ as the inverter can only modulate the voltage magnitude and not increase it above its nominal value. The limit to how much the synchronous speed can vary depends on the specific motor operation and is set through the limit values, ω_{max} and ω_{min} . The diagram view of the complete volts/hertz VSD model in Modelica is shown in Figure 9.

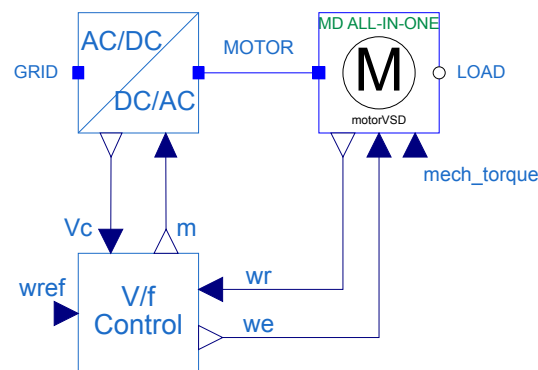


Figure 9. Diagram view of a complete VSD model.

The reader will notice several common input and output variables between the block diagram in Figure 8 and the Modelica model in Figure 9. The sensed motor rotor speed, w_r , which is an output in the MD motor model, is used as an input to the volts/hertz controller block, while an external angular reference (w_{ref}) determines the frequency/synchronous speed reference. The synchronous speed w_e and the PWM index m are calculated in the V/f control block, which is then used to control the magnitude and frequency of the voltage at the motor terminal. For more details on the modeling aspects of the Modelica ‘average’ VSD model from Figure 9, refer to [35].

5. Validation and Illustrative Results

To demonstrate the features of the developed models, the authors devised a set of simulations shown in this section. To verify that the results are consistent with the first-principles models/physics laws, we provide validation examples that test the behavior of the motor models. Furthermore, to present the innovative features suggested in this study, we offer illustrative examples. These examples encompass the operations of the variable

speed drive (VSD) and multi-domain system models, incorporating the power grid, motor, and fluid domains.

The simulations are divided into five different categories:

1. **Three-phase multi-domain motor validation example:** Evaluates the performance of all the three-phase multi-domain motors compared to the reference simulation results from the Power System Toolbox (PST).
2. **Three-phase non-multi-domain motor validation example:** Evaluates the performance of the CIM5 NMD motor compared to the reference simulation results from Siemens PTI PSS[®] E.
3. **VSD-controlled motor startup example:** Evaluates the performance of the VSD together with the three-phase MD motor for the case of a motor startup simulation.
4. **Multi-domain SPIM and DPIM examples:** Evaluates the performances of all MD variants of the single-phase induction motor (SPIM) and dual-phase induction motor (DPIM).
5. **Multi-domain system application example:** Demonstrates the capability of simulating multi-domain systems (power grid, multi-domain motor, and a fluidic system) in one holistic example.
6. **Microgrid example with multiple generation units and load models:** Demonstrates how the developed models can be integrated with a microgrid system example.

In all dynamic simulations exemplified in this section, we employ the DASSL solver (differential/algebraic system solver) [36]. This method is used for solving systems of differential-algebraic equations (DAEs). DASSL's key strength is in functionally handling stiff systems of differential-algebraic equations, which are prevalent in dynamic power system simulations.

5.1. Three-phase Multi-Domain Motor Validation Examples

To verify the accuracy of the three-phase MD induction motor models, we reproduced Example 11.7 from the book *Power System Modeling, Computation, and Control* by Chow et al. [37]. The authors of the book used the Power System Toolbox v3.0 (PST) [4], which is a MATLAB-based software, to perform a motor start simulation. The parameter values for the example are presented in Appendix B.

In the following study, we recreated the same system model as the one presented in [37], ensuring that all model parameters in the Modelica models matched precisely the reference models. The only modification made in both software environments was to use the *infinite bus* model to represent the grid. This adjustment was made to simplify the comparisons between the Modelica and PST-based models, i.e., to allow the excitation of the motor dynamics without any interference of other dynamic responses from other grid components. Figure 10 displays an example of the motor start in Modelica. No figure for the model in PST is available, as models in PST are defined through predefined data matrices and have no graphical schematic associated with them.

In Figure 10, the ALL-IN-ONE motor allows the user to simulate different MD three-phase motors simply by changing the selected motor model as a parameter. Meanwhile, the PST_Voltage, PST_Slip, PST_Pmotor, and PST_Qmotor components are lookup tables and are used to store the simulation results from PST to be used to compare with the Modelica model's response. Figure 11 presents a comparison between active and reactive power consumption, highlighting distinct behavior in *Motor1* when compared to the others. In Figure 11a, two noticeable oscillations in the active power consumption of *Motor3*, *Motor5*, *CIM*, and PST's model, are observed: one at the beginning of the simulation and another around $t = 2.35$ s. The oscillation at $t = 0$ originates from the modeling assumption that the initial voltage behind the stator resistance R_s is zero, i.e., $e'_{re}(0) = 0$ and $e'_{im}(0) = 0$. Linearization of the non-linear equations at $t = 0$ reveals a pair of complex eigenvalues that are stable (with a negative real component) and exhibit an oscillation frequency of 60.0684 Hz, confirming the observed oscillation in Figure 11. Since the active and reactive power signals of the PST serve as our reference points for comparing multi-

domain simulations, if the modified model can replicate the same response as the target value, we assume the correctness of the multi-domain model. However, as mentioned earlier, *Motor1* does not incorporate the dynamics associated with the flux linkage in the motor rotor. Consequently, the output response of this model differs from the reference and its more detailed counterparts.

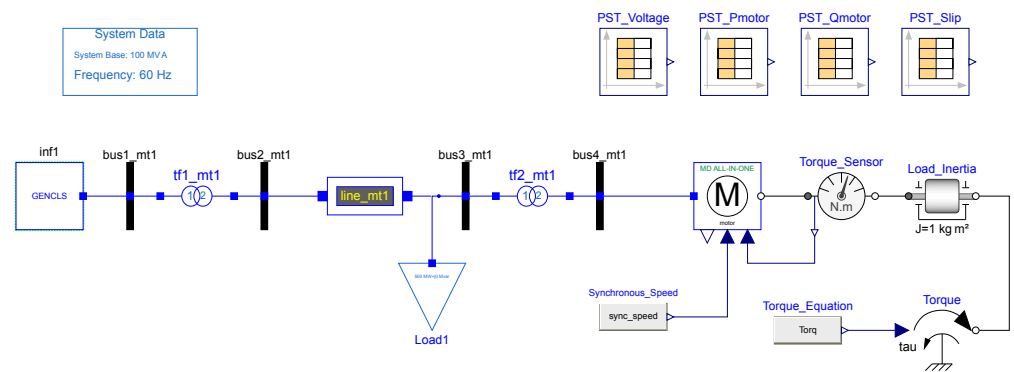
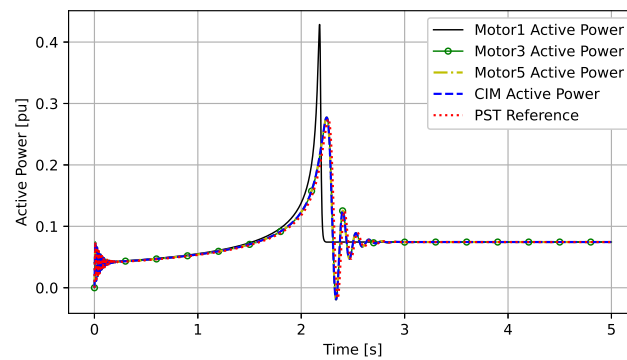
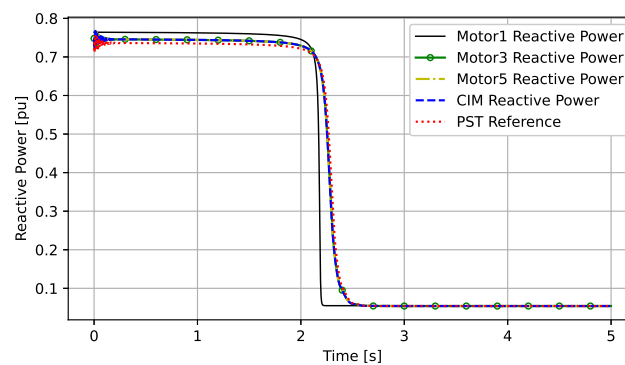


Figure 10. Multi-domain induction motor validation example.



(a)



(b)

Figure 11. Comparison between the induction motor simulation results and the PST reference: (a) active power; (b) reactive power.

Figure 12 displays the initial slip values over time for all MD three-phase induction motors modeled using the ALL-IN-ONE motor component, including the reference simulation result generated from PST.

In the context of simulating the induction motor startup process, the slip is initialized at $s = 1$ when $t = 0$ (representing the motor starting from a halted condition). As the rotor speed increases, the slip progressively decreases until it reaches its steady-state value of $s = 0.004$. Figure 12 clearly illustrates the distinctive behavior of *Motor1* in comparison

to other motors, especially as they approach their steady-state values. Note that *Motor1* exhibits no oscillatory behavior at around $t = 2.35$ s due to its modeling assumptions. Unlike *Motor3*, *Motor5*, *CIM*, and PST's model, *Motor1* does not include the rotor cage modeling, resulting in the simplest possible three-phase induction motor model. As a result, it does not factor in fluctuations in the flux linkage within the rotor and stator coils. *Motor1* is characterized by a single differential equation that describes the relationship between slip and torque, distinguishing it from the more detailed motor models. On the other hand, *Motor3*, *Motor5*, and *CIM* show similar results when compared to the reference model, confirming the validation process.

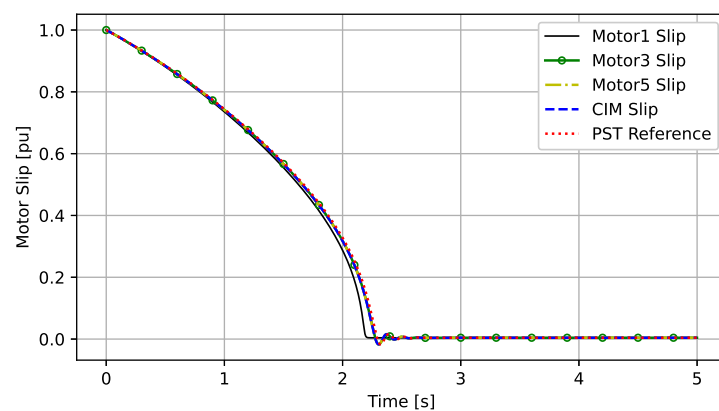


Figure 12. Comparison between the induction motor slip values and the PST reference.

The results depicted in this subsection align with the characteristics observed in Example 11.7 of [37], simulated using the PST v3.0 software tool [4].

5.2. Three-Phase Non-Multi-Domain Motor Validation Example

Section 5.1 presents the validation procedure and results for the three-phase MD motor models, in which their responses are compared with those obtained from the PST software. Because the MD motor models implemented can be coupled to Modelica rotational components, the load torque expression is defined outside of the motor component. Siemens PTI PSS[®] E, on the other hand, has different induction motor models, where each model contains a different load torque expression built into it. The load torque equation from the validation example shown in Section 5.1 differs from the expression defined by the motor models CIM5 and CIM6 in PSS[®] E; therefore, this section is meant to compare the non-multi-domain motor models implemented against the reference software, PSS[®] E. To keep it concise, this section presents only the verification results that compare the implementation of the CIM5 model with PSS[®] E. The NMD CIM5 validation model is similar to the one presented in Figure 10; the sole difference is that there is no flange in the model and, thus, no mechanical interface components. For this reason, the graphical representation of the Modelica model is not shown in this section, although the parameter values for the validation example are presented in Appendix B. Figures 13 and 14 show the active and reactive power consumption of the CIM5 motor model and its slip curve compared to the reference simulation obtained using PSS[®] E. Similar to the previous section, the results displayed here point to the accuracy of the induction motor model implemented in Modelica.

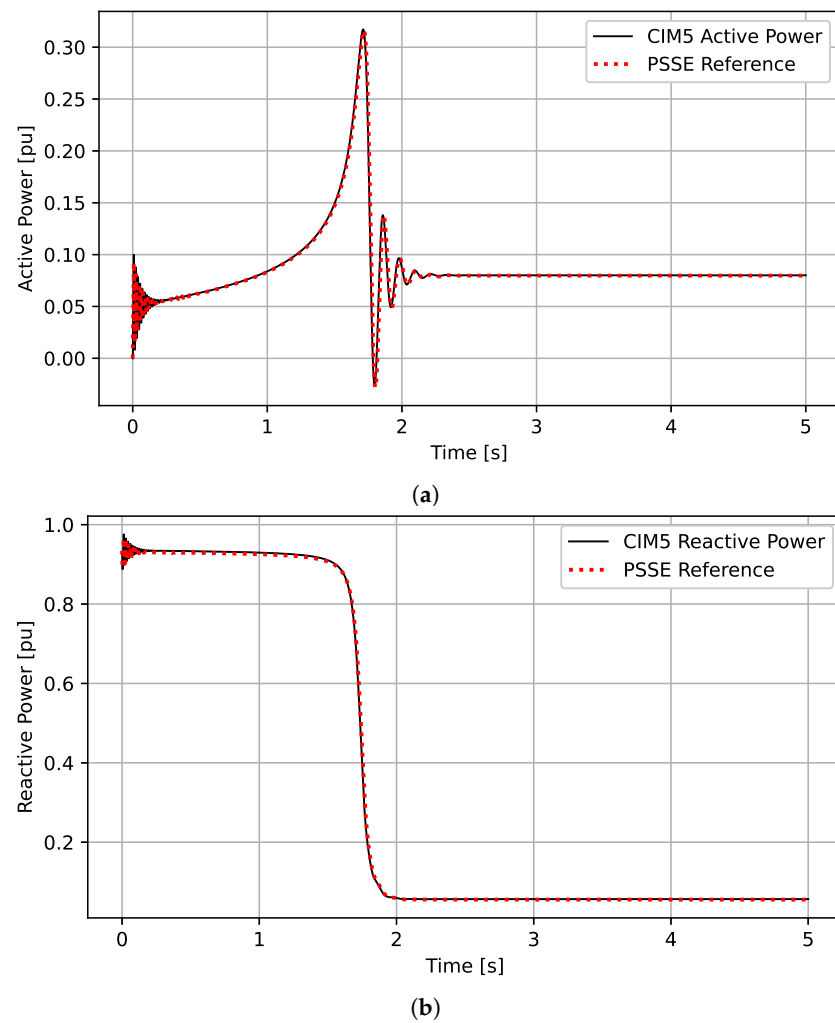


Figure 13. Comparison between the induction motor simulation results and PSS® E reference: (a) active power; (b) reactive power.

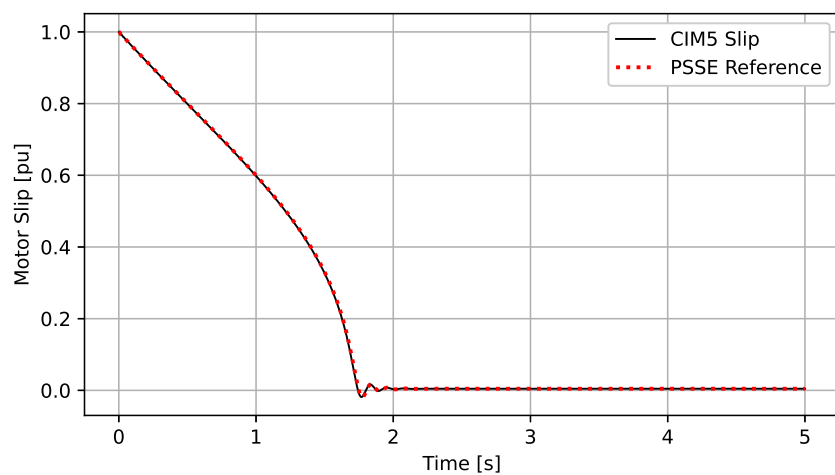


Figure 14. Comparison between the induction motor slip values and the PSS® E reference.

5.3. VSD-Controlled Motor Startup Example

In this example, a three-phase multi-domain motor model is simulated in two similar system models, as shown in Figure 15, where one model includes a VSD controller (top) and the second one does not (bottom). Observe that the power system is modeled using OpenIPSL components (components to the left of buses *bus4_mt1* and *bus4_mt2*), followed by the components described in this paper. The system models were built based on Example 11.7 from [37], and the parameter values for the aforementioned example are presented in Appendix C.

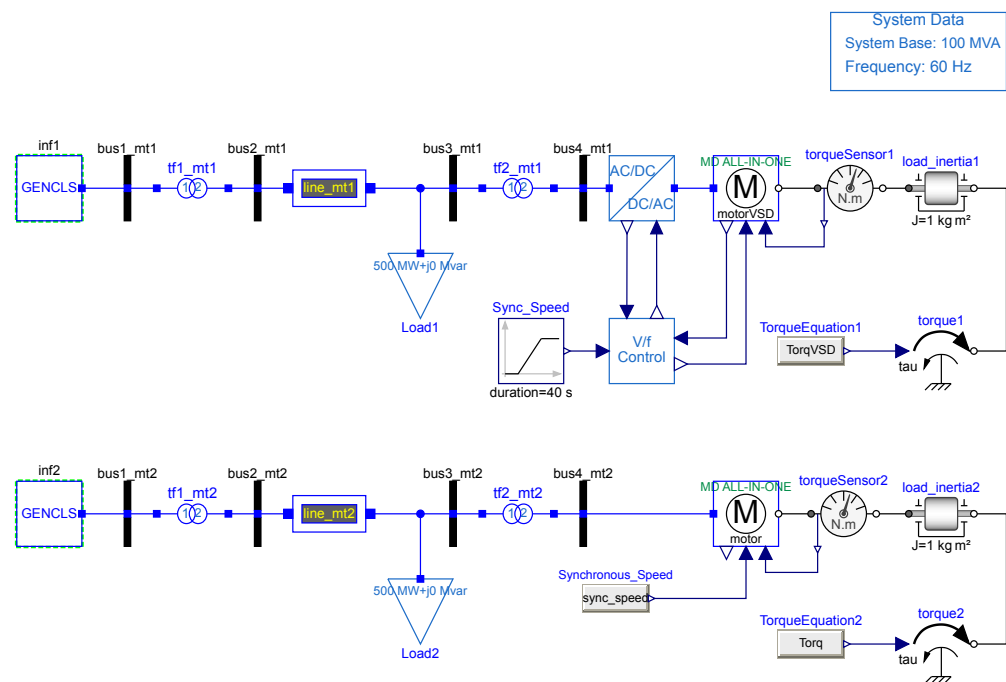


Figure 15. VSD startup multi-domain induction motor comparison example.

The goal of this example is to show the impact of having a VSD on the motor startup process. The novelty shown in this example is the capability to vary the synchronous speed and terminal motor voltage in order to control the startup process, as well as having models that span multiple domains, which is not possible with power system simulation tools. The motor startup process involves gradually ramping up the synchronous speed and terminal voltage, resulting in reduced current draw from the motor during startup.

Figure 16 displays the current magnitude drawn by the Type III MD model connected to a VSD compared to the motor connected to the grid. For the sake of clarity in the plots, the authors show only one comparison example utilizing a Type III MD motor model. The red curve presents the current magnitude of the motor in the system without VSD, while the blue curve reflects the current magnitude of the motor in the system with VSD. The case with VSD displays a significantly smaller current magnitude during the startup process, which is set for 5 s. For this particular example, the voltage and synchronous speed increase at the same rate for a duration of 5 s until a peak voltage value of 1 p.u. and a frequency of 60 Hz (equivalent to achieving a synchronous speed of $2\pi f$ rad/s). The spike in the blue torque curve demonstrates the transient response of the motor as the voltage and frequency increase, while the constant torque value after transient, from $t = 1.5$ s to $t = 5$ s, reflects the constant torque region of the motor with the variable voltage and variable frequency power supply. The red curve corresponds to the electromagnetic torque of the Type III motor connected to the grid with no VSD startup control. As expected, the VSD-driven motor experiences a constant torque during the startup process (after its initial transient), which is higher than the grid-connected motor. It is worth pointing out that the mechanical torque in both scenarios also changes; a higher initial motor torque from a halted position

results in a counter-mechanical torque that is proportional to the applied force. For that reason, in Figure 17, the mechanical torque in the case with VSD (yellow dashed curve) is greater than the mechanical torque in the motor without VSD (green dashed curve).

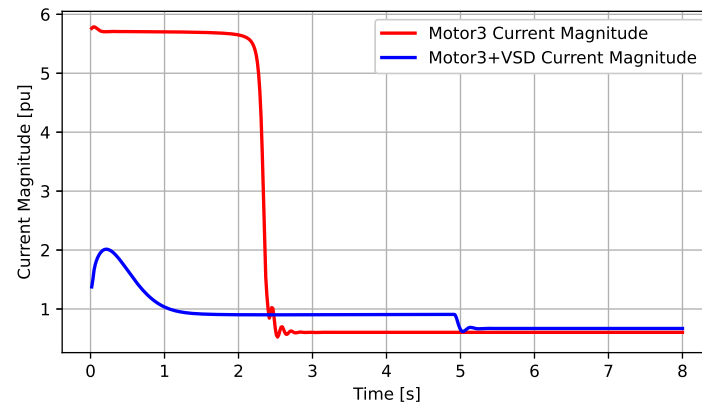


Figure 16. Startup current comparison.

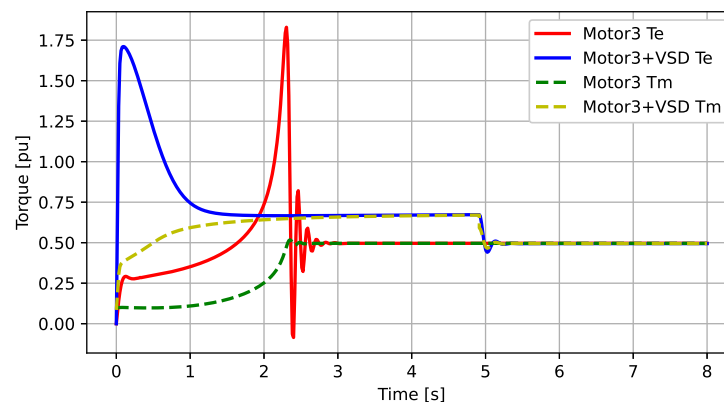


Figure 17. Mechanical and electromagnetic torque comparison.

5.4. Multi-Domain SPIM and DPIM Motor Model Validation Examples

In these examples, validation of the multi-domain SPIM and DPIM motor models is conducted through three different simulation scenarios that are designed to demonstrate the steady-state and startup operations of the SPIM and DPIM motor models.

As mentioned in Section 3.3, the SPIM motor model is intended to simulate post-startup scenarios, where the motor start process is not of interest and the user wants to initialize the simulation from its steady-state operation. To test the steady-state operation of the motor, the validation is carried out using the SPIM model, as shown in Figure 18, while the parameter values for this particular example are found in Appendix D.

This example is constructed in a way that the VariableTorque component will act like a ramp, linearly increasing the load torque applied to the motor until it reaches a new steady state condition. Figure 19 displays the result of the SPIM example simulation for a duration of 5 s. The red curve displays the electromagnetic torque of the SPIM model, while the blue curve displays the slip of the motor model. Initially, the plots of both curves in an interval of $t = 0$ to $t = 1$ start flat, which means that the simulation is initialized in a steady-state condition. From $t = 1$ to $t = 4$ s, the mechanical torque increases, and as such, the electromagnetic torque of the SPIM motor must increase to maintain the motor operation. Consequently, the slip also increases, which confirms that the motor under increasing loads has a reduction in the rotor speed. It is worth mentioning that in the circuit of Figure 18, the electrical system from the load_bus to the left represents one of the three phases of a three-phase electrical grid, which means that the model can emulate the

operation of a single-phase induction motor in a single-phase electrical circuit common to North American households.

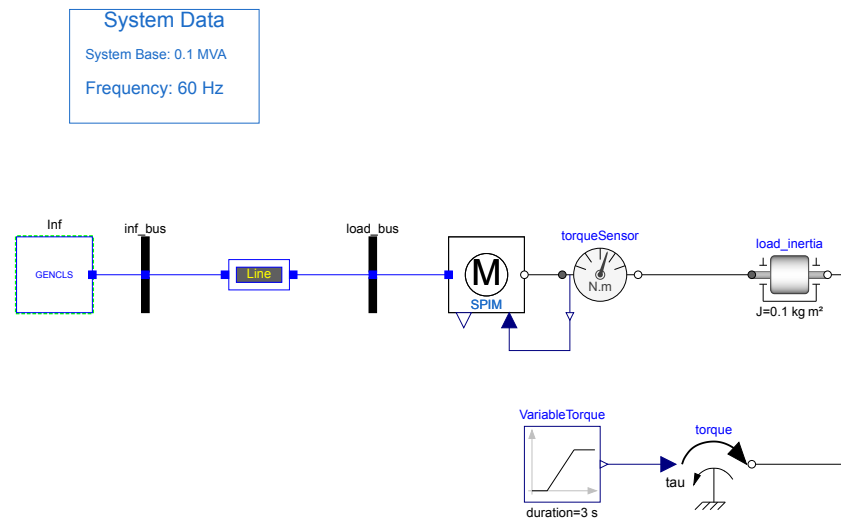


Figure 18. Multi-domain SPIM model validation example.

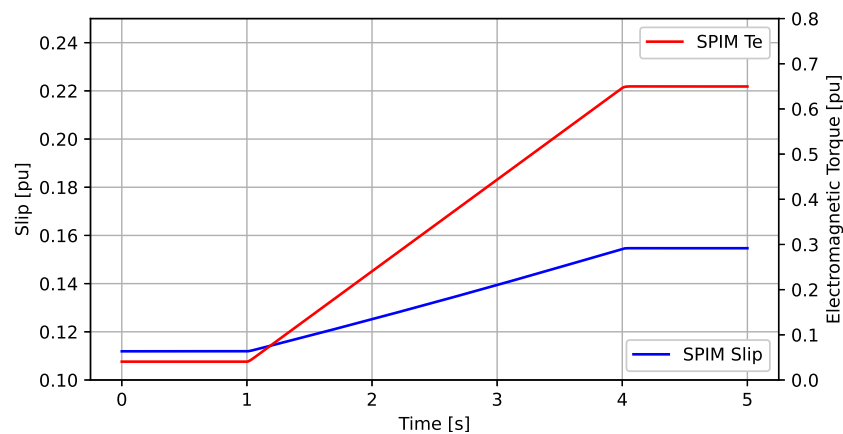


Figure 19. SPIM electromagnetic torque (T_e) and slip characteristics.

To test the startup dynamics of the single-phase induction motor, the validation is conducted utilizing the DPIM model. The model configuration closely resembles the one depicted in Figure 18, with the only distinction being the utilization of a DPIM motor model.

The developed DPIM model can model both a split-phase dual-phase and a capacitor-start dual-phase induction motor (their differences are highlighted in Section 3.3.2). Figure 20 displays the electromagnetic torque of the split-phase and capacitor-based startup configurations.

As expected, the capacitor-start DPIM motor is configured to experience a 90-degree shift between the main and auxiliary winding circuits, which consequently generates a higher startup torque versus the split-phase scheme. The black dashed curve displays the electromagnetic torque for the capacitor start, whereas the red solid curve represents the split-phase startup. In both cases, the auxiliary circuit is turned off once the slip reaches a predefined value of 0.1 [p.u.], in which case, the torque reduces to a value that the main stator winding can generate. It is worth mentioning that the results are consistent with the description in Chapter 9, Sections 9.2.1 and 9.2.2 of the book *Electrical Machinery* by Fitzgerald et al. [27].

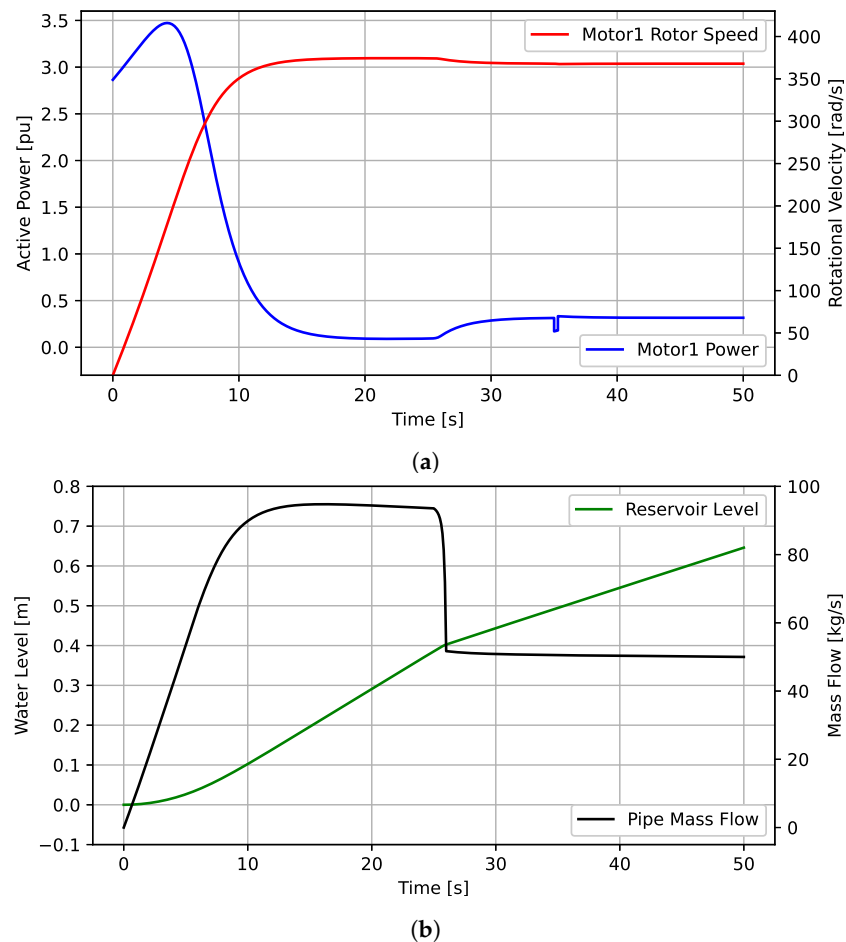


Figure 22. Simulation results: (a) motor active power and rotor speed; (b) load reservoir level and pipe mass flow.

In this case study, the obstruction in the pipe starts to emerge at $t = 25$ s, clogging 90% of the pipe in 1 s. An electrical fault is set to occur at $t = 35$ s, for a duration of 0.3 s. The obstruction reduces the cross-section area of the pipe to 10%, increasing the load torque and, consequently, increasing the power drawn by the motor. The increase in power comes with a reduction in rotor speed (see the red curve in Figure 22a). Due to the electrical fault, the motor's terminal voltage decreases, which consequently reduces the power drawn by the motor momentarily. Once the electrical fault is cleared, the motor returns to its previous state. Note that given the short electrical fault duration, there is no major impact on the hydraulic behavior (pipe mass flow and reservoir level). Thus, this example shows the value of expanding modeling capabilities beyond conventional scenarios common to power system tools.

5.6. Microgrid Example with Multiple Generation Units and Load Models

This example demonstrates how the developed models can be integrated with a microgrid. To model the grid, the OpenIPSL Library provides different generation sources, load models, and other component models, which together with the models developed in this manuscript, can be combined into a single and unified simulation model. In addition, we extend the model with a fluid sub-system, illustrating how the integrated model allows simulating the electrical, mechanical, and fluidic domains simultaneously within a single software environment.

The developed example is shown in Figure 23, representing a microgrid connected to the utility grid through a single point of common coupling (PCC).

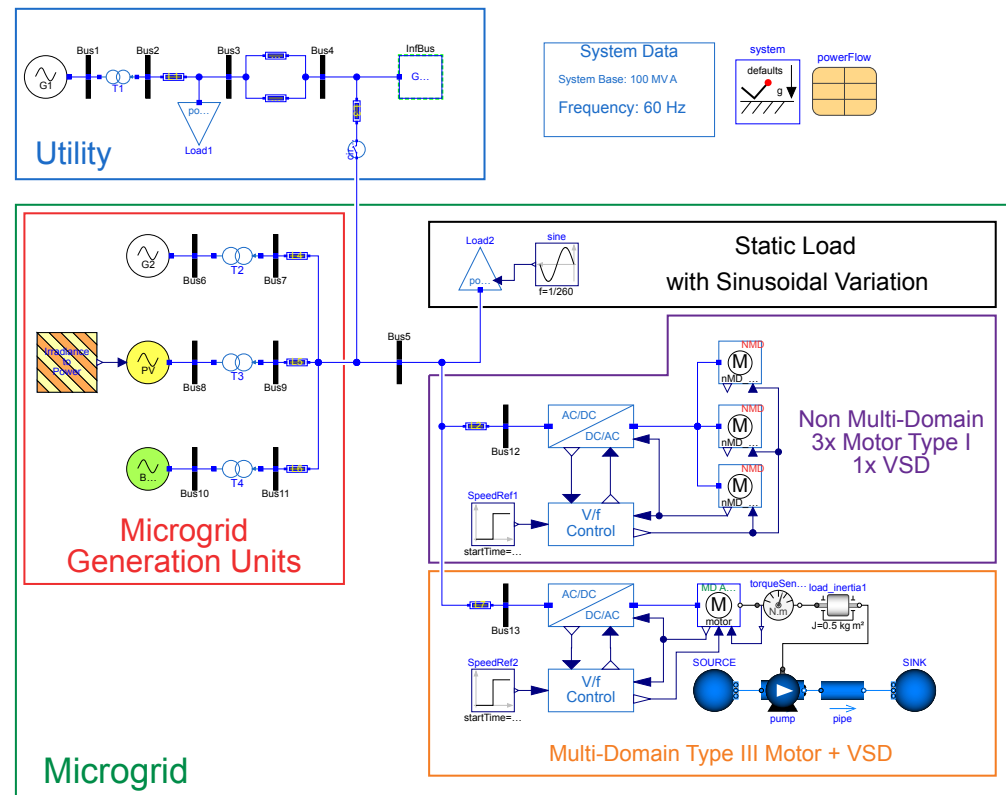


Figure 23. Microgrid system example with multiple generation units and multiple load sources.

The microgrid is represented by the system inside the green solid line, while the utility grid is represented by the system in the blue solid line. The microgrid consists of various generation units, including a combustion-based turbine-driven generator system, a photovoltaic (PV) plant, and a battery energy storage system (BESS) unit. The PV plant contains an irradiance-to-power block that allows to model of the variability of the injected DC going from PV cells/array. The synchronous generator is equipped with a primary-level control system comprising a speed governor and an automatic voltage regulator (AVR), while renewable sources have active and reactive power controls. All components responsible for energy production within the microgrid are categorized as distributed energy resources (DERs). DERs are small-scale energy sources typically located near the point of use or within the distribution network, with an energy production limit of 10 MW [40]. For this study, the synchronous generator in the microgrid has a capacity of 10 MW, while the rated active power of renewable energy sources is 5 MW. Lastly, the microgrid presents a mix of static and dynamic loads. The dynamic loads are a mix of the multi-domain motor and non-multi-domain motor models, including motor speed control with VSDs, which were presented in this paper. The static load represents the usual residential/commercial electrical loads.

The utility grid model includes a section of the power distribution system, a hydropower plant, and the remaining grid infrastructure. In this study, the synchronous generator serves as the primary energy source determining the voltage and frequency within the microgrid, while the renewable DERs function as “grid-following” components.

This example expands on the simulation capabilities demonstrated in the previous example from Section 5.5. It incorporates multiple motor philosophies, a grid, and a grid-connected microgrid into a single example. The static load includes a sinusoidal component, resulting in a sinusoidal variation in the active power consumption of the load.

In the context of motors, the non-multi-domain motors simulate a ventilation system, where one variable speed drive (VSD) controls the speed of three identical motors. In contrast, the multi-domain Type III motor represents a water pumping unit, which in this example could represent the water pumping station of a campus microgrid, for instance.

Overall, this example illustrates how—by using the developed models in this work—a user could now simulate multiple domains simultaneously.

In this example, the following sequence of events is applied to illustrate the model's features, as follows:

- **Event 1:** At $t = 10$ s, a reduction of 30% of the reference speed ω_{ref} of the VSD that controls the three non-multi-domain motors is applied. The reduction in ω_{ref} decreases both the motor terminal voltage magnitude and frequency, thus also reducing the power consumption.
- **Event 2:** At $t = 20$ s, a reduction of 25% in the reference speed ω_{ref} of the VSD that controls the multi-domain motor is applied. Similar to Event 2, the multi-domain motor will also experience a reduction in power consumption.
- **Event 3:** At $t = 30$ s, a reduction of 50% in irradiance levels (from 666.66 W/m^2 to 333.33 W/m^2) is applied to the solar PV plant. This results in a 50% reduction of the injected power from the PV generation unit.
- **Event 4:** At $t = 40$ s, the circuit breaker tripping signal at the point of common coupling (PCC) is triggered, causing the microgrid to become isolated from the utility grid. Before isolation, the microgrid imported 3.3 MW of power from the utility, resulting in a power imbalance. Consequently, the overall frequency of the microgrid falls below the nominal value of 60 Hz during the islanding scenario.

Figure 24 showcases the simulation results for the microgrid system that withstood the four events detailed above.

When the microgrid becomes islanded at $t = 40$ s, the system loses approximately 4 MW of power from the utility grid (as seen in Figure 24a). The primary controllers of the microgrid generation units lack the capability of eliminating the frequency error (which is the task of the secondary level controller); thus, immediately after the circuit breaker trip, microgrid frequency displays a dip and reaches a new steady-state value of around 59.35 Hz (as seen in Figure 24e). Microgrid active power import is related to how much power the microgrid itself can generate; thus, at $t = 30$ s, when there is a reduction in irradiance levels, the amount of imported power must increase to balance power (as seen in Figure 24a). In Events 1 and 2, there is a reduction in the reference speed of the VSDs of all the induction motors involved in the simulation. The VSD reduces both the voltage magnitude and input frequency, leading to reduced power consumption (as seen in Figure 24b,c). Consequently, the pump operates at a reduced rotational speed and the mass flow in the water system is also reduced proportionally (as seen in Figure 24d).

These simulation results illustrate what is possible to study using multi-domain modeling, as enabled by the models developed in this paper, integrating them with models from the Modelica Standard Library and OpenIPSL.

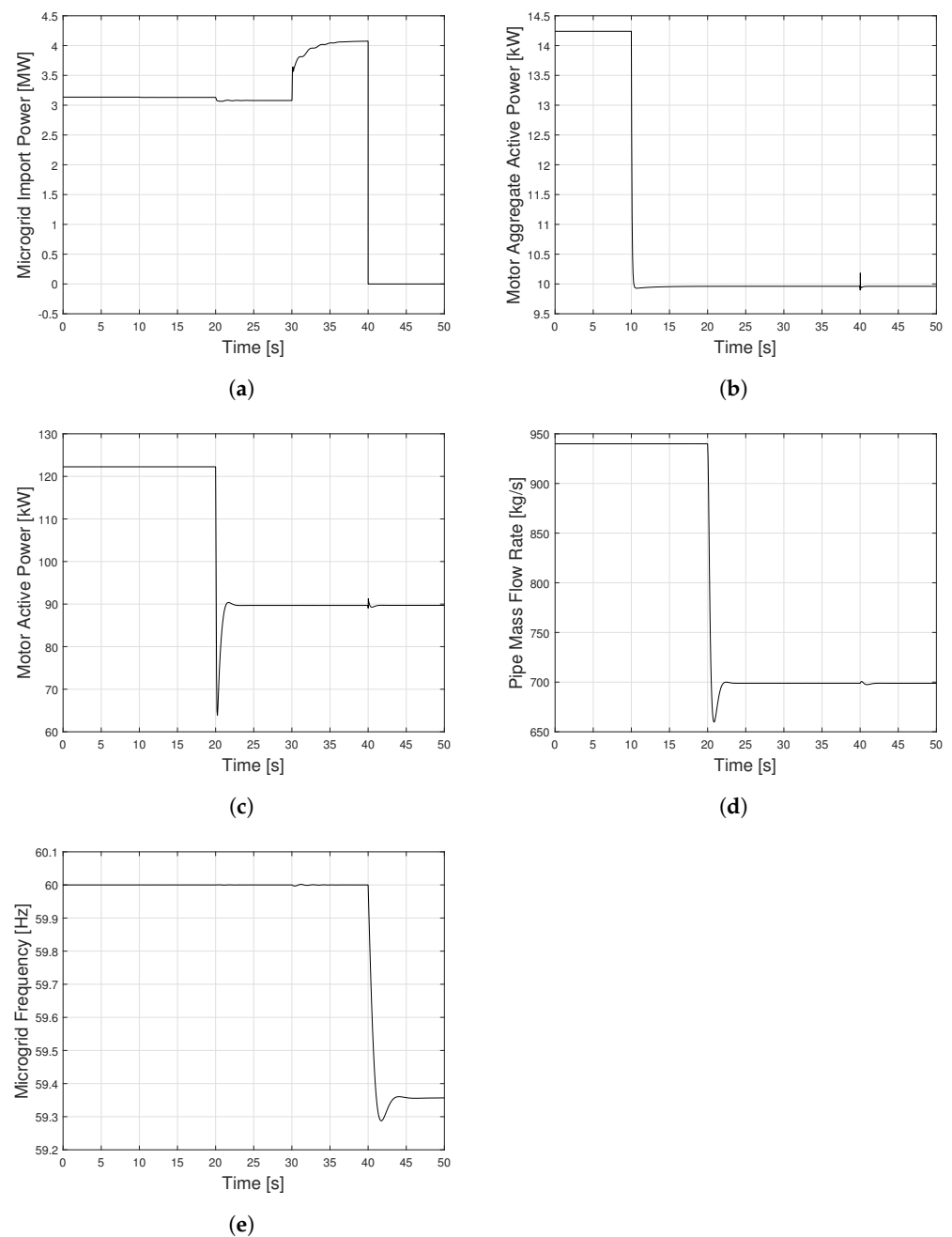


Figure 24. Simulation results: (a) microgrid active power import; (b) total active power consumption from the three non-multi-domain induction motors; (c) total active power consumption of the multi-domain motor; (d) water system mass flow rate; (e) microgrid frequency.

6. Conclusions

This work presents the development, implementation, and validation of multi-domain and non-multi-domain three-phase and single-phase motor models that are voltage-/frequency-controlled and, thus, can be coupled to a VSD model. The set of implemented motor models, along with the VSD, was developed to address a gap in traditional phasor domain power system modeling, enabling both rotational speed controllability over motor models as well as the ability to enrich the representation of the load processes coupled to the mechanical dynamics of the motor. Consequently, the new phasor domain motor models can now be coupled with detailed representations of the driven load, giving unique modeling capabilities that are unavailable in standard power system simulation tools, which only use a simplified torque equation to represent them. Simulation studies showed

that the developed components are crucial for the detailed study of multi-domain systems, such as the electrical and hydraulic systems.

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Data Availability Statement: The GitHub repository containing all the models and validation tests presented in this work can be found here: <https://github.com/ALSETLab/OpenIMDML> (accessed on 16 April 2024).

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Abbreviations

The following abbreviations are used in this manuscript:

AC	alternate current
CHP	combined heat and power
DC	direct current
DPIM	dual-phase induction motor
GE	General Electric
MD	multi-domain
MSL	Modelica Standard Library
NMD	non-multi-domain
OpenIPSL	Open Instance Power System Library
PSAT	Power System Analysis Toolbox
PST	Power System Toolbox
VSD	variable speed drive
WECC	Western Electric Coordinating Council

Appendix A. Induction Motor Model Type III Parameters and Variables

1. `w_sync`: Synchronous speed variable toggled to either utilize the system nominal frequency parameter `w_b` or the input connection port `we`.
2. `Ctrl`: Boolean parameter that allows the user to choose between the controllable if `Ctrl == true` or non-controllable if `Ctrl == false`. If `Ctrl == true`, then motor impedance and motor frequency will vary based on an input value from the connector `we`, or else the motor frequency will be determined by `w_b`, which is the nominal system frequency in rad/s.

3. **we**: Modelica input connector for inputting the motor's synchronous speed. In the case where `Ctrl == false`, the connector is eliminated from the model.
4. **s**: Induction motor slip, defined by the ratio between the difference in rotor and synchronous speeds to the synchronous speed of the rotating magnetic field. This variable is unitless.
5. **w_b**: Base frequency parameter, defined as $w_b = 2\pi f_n$ [rad/s], where $f_n = 60$ [Hz].
6. **Vr**: Real component of the motor terminal voltage, expressed in per unit [p.u.], on the system base.
7. **Vi**: Imaginary component of the motor terminal voltage, expressed in per unit [p.u.], on the system base.
8. **Ir**: Real component of the motor consumed current, expressed in per unit [p.u.], on the system base.
9. **Ii**: Imaginary component of the motor consumed current, expressed in per unit [p.u.], on the system base.
10. **pwpin**: Ubiquitously used connector from OpenIPSL that contains four variables: two potential $\{pwpin.vr, pwpin.vi\}$ and two flow $\{pwpin.ir, pwpin.ii\}$ variables [41].
11. **mech_torque**: Mechanical torque in the Newton meter [N.m], which is both the input connector and a motor equation variable.
12. **T_b**: Base torque [N.m] of the system.
13. **Tmech_pu_sys**: Mechanical torque variable, expressed in per unit [p.u.], on the system base.
14. **Tmech_pu_motor**: Mechanical Torque variable, expressed in per unit [p.u.], on the motor base.
15. **S_b**: System apparent power base.
16. **Xs**: Stator winding impedance, expressed in per unit [p.u.], on the motor base.
17. **Xm**: Magnetization impedance, expressed in per unit [p.u.], on the motor base.
18. **X1**: Rotor winding impedance, expressed in per unit [p.u.], on the motor base.
19. **X0**: The sum of the stator impedance and the magnetization impedance, expressed in per unit [p.u.], on the motor base. In the case where `Ctrl == false`, the induction motor is not controllable and, thus, the impedance parameter is constant. If `Ctrl == true`, the induction motor is indeed controllable, and the impedance parameter is determined via the frequency ratio, $\frac{weX0}{w_b}$.
20. **Xp**: The sum of the stator impedance and the parallel impedance $Xm \parallel X1$, expressed in per unit [p.u.], on the motor base. In the case where `Ctrl == false`, the induction motor is not controllable and, thus, the impedance parameter is constant. If `Ctrl == true`, the induction motor is indeed controllable, and the impedance parameter is determined via the frequency ratio, $\frac{weXp}{w_b}$.
21. **Tp0**: Defines the open-circuit time constant of the induction motor [s]. In the case where `Ctrl == false`, the time constant is fixed, while if `Ctrl == true`, the induction motor time constant is determined via the frequency ratio, $\frac{weTp0}{w_b}$.
22. **epr**: Real component of the voltage behind the stator resistance, r_s , also known as the direct transient magnetization voltage.
23. **epm**: Imaginary component of the voltage behind the stator resistance, r_s , also known as the quadrature transient magnetization voltage.

Appendix B. Non-Multi-Domain and Multi-Domain Motor Startup System Parameters

Table A1. Example Parameter Values.

Component	Parameter	Value	Unit
Inf1	Machine Base (M_b)	600	MVA
	Inertia (H)	0	s
	Damping (D)	0	p.u.
	Armature Resistance (R_a)	0	p.u.
	d-axis reactance (X_d)	0	p.u.
bus1_mt1	Base Voltage (V_b)	16	kV
	Voltage Magnitude (V_0)	1.05	p.u.
	Angle (angle_0)	0	°
bus2_mt1	Base Voltage (V_b)	230	kV
	Voltage Magnitude (V_0)	1.03	p.u.
	Angle (angle_0)	−6.739	°
bus3_mt1	Base Voltage (V_b)	230	kV
	Voltage Magnitude (V_0)	1.023	p.u.
	Angle (angle_0)	−12.666	°
bus4_mt1	Base Voltage (V_b)	23	kV
	Voltage Magnitude (V_0)	1.015	p.u.
	Angle (angle_0)	−12.882	°
tf1_mt1	Sending End Voltage (V_b)	16	kV
	Voltage Rating (Vn)	16	kV
	Resistance (rT)	0	p.u.
	Reactance (xT)	0.025	p.u.
tf2_mt1	Sending End Voltage (V_b)	230	kV
	Voltage Rating (Vn)	230	kV
	Resistance (rT)	0	p.u.
	Reactance (xT)	0.15	p.u.
line_mt1	Resistance (R)	0	p.u.
	Reactance (X)	0.02	p.u.
	Shunt Half Conductance (G)	0	p.u.
	Shunt Half Susceptance (B)	0	p.u.
Load1	Initial Active Power (P_0)	500	MW
	Initial Reactive Power (Q_0)	0	Mvar
	Voltage Magnitude (V_0)	1.023	p.u.
	Angle (angle_0)	−12.666	°
Multi-Domain/Non-Multi-Domain	Machine Base (M_b)	15	MVA
	Number Pair Poles (N)	1	-
	Inertia Constant (H)	0.4	s
	Stator Resistance (Rs)	0	p.u.
	Stator Reactance (Xs)	0.0759	p.u.
	1st Cage Rotor Resistance (R1)	0.0085	p.u.
	1st Cage Rotor Reactance (X1)	0.0759	p.u.
	Magnetization Reactance (Xm)	3.1241	p.u.
load_inertia1	Moment of Inertia (J)	1	kg·m ²
Torque Equation	Torque (PST)	$0.1s + 0.5(1 - s)^2$	N·m
	Torque (PSS [®] E)	$0.534(1 - s)^2$	p.u. Machine Base
Synchronous_Speed	sync_speed	2π60	rad/s

Appendix C. VSD-Controlled Motor Startup System Parameters

Table A2. Example Parameter Values.

Component	Parameter	Value	Unit
Inf1/Inf2	Machine Base (M_b)	600	MVA
	Inertia (H)	0	s
	Damping (D)	0	p.u.
	Armature Resistance (R_a)	0	p.u.
	d-axis reactance (X_d)	0	p.u.
bus1_mt1/bus1_mt2	Base Voltage (V_b)	16	kV
	Voltage Magnitude (V_0)	1.05	p.u.
	Angle (angle_0)	0	°
bus2_mt1/bus2_mt2	Base Voltage (V_b)	230	kV
	Voltage Magnitude (V_0)	1.03	p.u.
	Angle (angle_0)	−6.739	°
bus3_mt1/bus3_mt2	Base Voltage (V_b)	230	kV
	Voltage Magnitude (V_0)	1.023	p.u.
	Angle (angle_0)	−12.666	°
bus4_mt1/bus4_mt2	Base Voltage (V_b)	23	kV
	Voltage Magnitude (V_0)	1.015	p.u.
	Angle (angle_0)	−12.882	°
tf1_mt1/tf1_mt2	Sending End Voltage (V_b)	16	kV
	Voltage Rating (Vn)	16	kV
	Resistance (rT)	0	p.u.
	Reactance (xT)	0.025	p.u.
tf2_mt1/tf2_mt2	Sending End Voltage (V_b)	230	kV
	Voltage Rating (Vn)	230	kV
	Resistance (rT)	0	p.u.
	Reactance (xT)	0.15	p.u.
line_mt1/line_mt2	Resistance (R)	0	p.u.
	Reactance (X)	0.02	p.u.
	Shunt Half Conductance (G)	0	p.u.
	Shunt Half Susceptance (B)	0	p.u.
Load1/Load2	Initial Active Power (P_0)	500	MW
	Initial Reactive Power (Q_0)	0	Mvar
	Voltage Magnitude (V_0)	1.023	p.u.
	Angle (angle_0)	−12.666	°
motor/motorVSD	Machine Base (M_b)	15	MVA
	Number Pair Poles (N)	1	-
	Inertia Constant (H)	0.4	s
	Stator Resistance (Rs)	0	p.u.
	Stator Reactance (Xs)	0.0759	p.u.
	1st Cage Rotor Resistance (R1)	0.0085	p.u.
	1st Cage Rotor Reactance (X1)	0.0759	p.u.
	Magnetization Reactance (Xm)	3.1241	p.u.
load_inertia1/load_inertia2	Moment of Inertia (J)	1	kg·m ²
Torque_Equation	Torq	$0.1s + 0.5(1 - s)^2$	N·m
	TorqVSD	$0.1s + 0.5(1 - s)^2$	N·m
Synchronous_Speed	sync_speed	$2\pi 60$	rad/s

Appendix D. SPIM/DPIM Validation Example System Parameters

Table A3. Example Parameter Value.

Component	Parameter	Value	Unit
Inf	Machine Base (M_b)	100	MVA
	Inertia (H)	0	s
	Damping (D)	0	p.u.
	Armature Resistance (R_a)	0	p.u.
	d-axis reactance (X_d)	0	p.u.
inf_bus	Base Voltage (V_b)	230	V
	Voltage Magnitude (V_0)	1.0	p.u.
	Angle (angle_0)	0	°
load_bus	Base Voltage (V_b)	230	V
	Voltage Magnitude (V_0)	0.999	p.u.
	Angle (angle_0)	0.016	°
SPIM	Machine Base (M_b)	3.5	kVA
	Base Voltage (V_b)	230	V
	Number Pair Poles (N)	1	-
	Inertia Constant (H)	0.1	s
	Stator Winding Resistance (R1)	0.01	p.u.
	Rotor Winding Resistance (R2)	0.05	p.u.
	Stator Winding Reactance (X1)	0.01	p.u.
	Rotor Winding Reactance (X2)	0.01	p.u.
	Magnetization Reactance (Xm)	0.1	p.u.
DPIM	Machine Base (M_b)	3.5	kVA
	Base Voltage (V_b)	230	V
	Number Pair Poles (N)	1	-
	Inertia Constant (H)	0.1	s
	Aux Winding cut-off speed (switch_open_speed)	0.1	-
	Mutual-inductance of the main winding (Lmainr)	0.6	mH
	Self-inductance of the magnetizing branch (Lmain)	0.0860	H
	Mutual-inductance of the auxiliary winding (Lauxr)	0.9	mH
	Self-inductance of the auxiliary winding (Laux)	0.1960	H
	Self-inductance of the equivalent rotor windings (Lr)	4.7	μH
	Resistance of the main winding (Rmain)	0.58	Ω
	Resistance of the rotor winding (Rr)	0.0376	mΩ
	Resistance of the auxiliary winding (Raux)	3.37	Ω
	Capacitance of the capacitor-start (Cc)	0.3	mF
load_inertia	Moment of Inertia (J)	0.1	kg·m ²
VariableTorque	InitialTorque	0.041	p.u.
	FinalTorque	0.649	p.u.
	startTime	1	s
	duration	3	s

Appendix E. Induction Motor Steady-State Model Diagrams

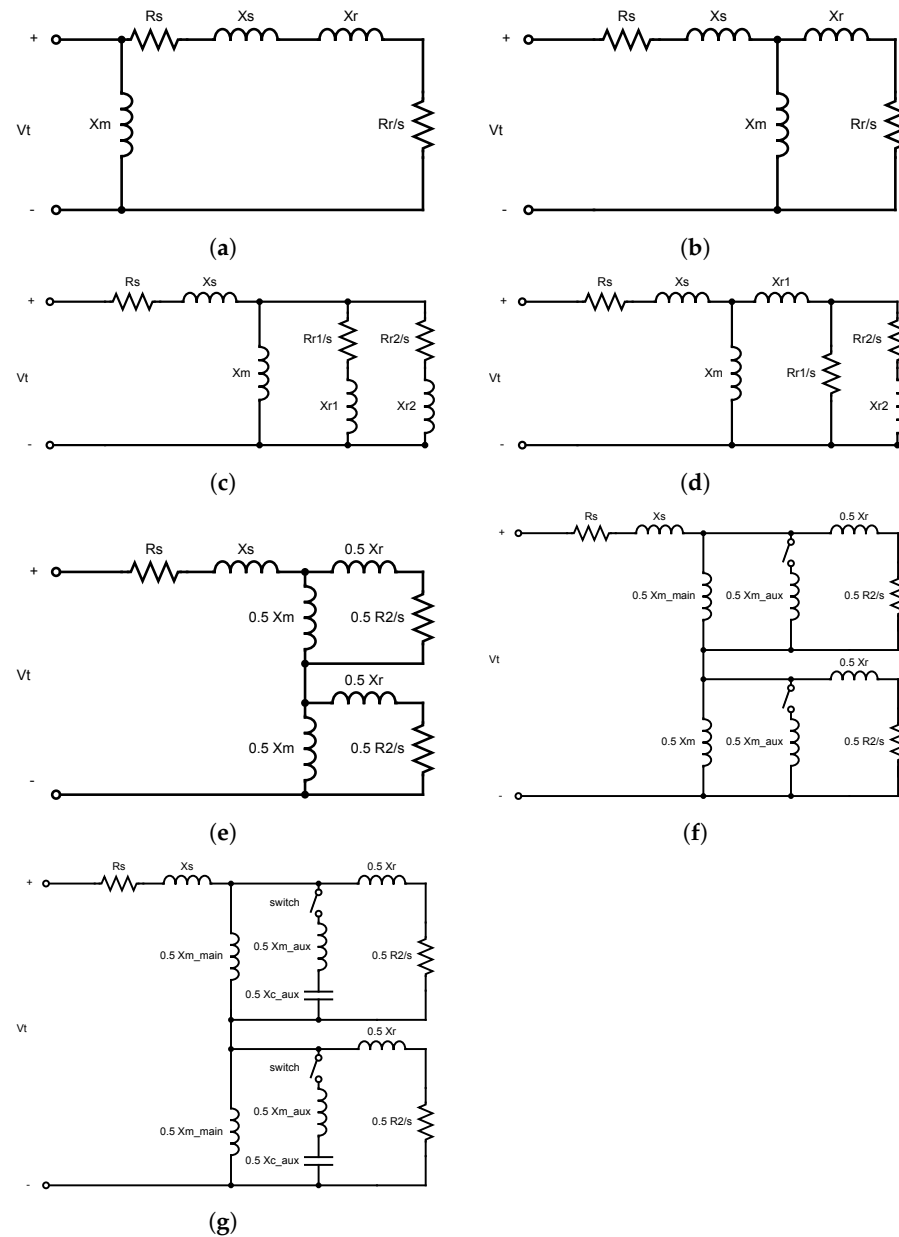


Figure A1. Electrical circuit for different induction motor models. (a) Electrical circuit for the PSAT-based three-phase induction motor type I. (b) Electrical circuit for the PSAT-based three-phase induction motor type III. (c) Electrical circuit for the PSAT-based three-phase induction motor type V, PSS® E CIM5, and CIM6 Type (A). (d) Electrical Circuit for the three-phase PSS® E CIM5, and CIM6 Type (B). (e) Electrical circuit for the single-phase induction motor. (f) Electrical Circuit for the split-phase dual-phase induction motor. (g) Electrical circuit for the capacitor-start dual-phase induction motor.

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