

Power Hardware-In-The-Loop approach in power system development

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Abstract—The main objective of the research is the verification of the Power Hardware-In-The-Loop (PHIL) approach in power system analysis and design. The premise of the article is that using PHIL approach the performance of the power system in steady and transient state conditions can be analysed in real power system conditions. Models of induction machine were developed and real time simulations were performed. Simulation variables were then used in power inverter control algorithm so that the terminal behaviour of the inverter was as the one of the developed model. This allows for the performance analysis of unlimited number of scenarios.

I. INTRODUCTION

In recent years Real-Time Simulations (RTS) including Model In The Loop (MIL), Software in the Loop (SIL), Hardware in the Loop (HIL) and other variants gained great attention from researchers and industry alike. The reason for this is most evident in all fields driven by two major factors: short life cycle of a product and complexity of its design. However there are more benefits visible in the development cycle, such as: increased safety, enhanced quality and the human factor. RTS can be divided into two groups: completely digital real-time simulations (e.g. MIL, SIL) and hardware in the loop (HIL) real-time simulation. A fully digital real-time simulation represents the entire system inside the simulator and does not include external interfaces. On the other hand, the HIL simulation refers to the condition where parts of the fully digital real-time simulation have been replaced with actual physical component [1].

The electrical machine or physical part of the system (called the plant) is normally connected with the control system, through actuators and sensors. With HIL testing the plant is replaced by a simulation of the plant (called the HIL simulator). If the HIL simulator is designed well, it will accurately mimic the plant, and can be used to test the control system. Some HIL simulators are equipped with visualization tools and represent the plant so well that they can be used for training. Moreover, with HIL approach more extreme scenarios may be performed, that would otherwise destroy a real plant or would be harmful for people in a real situation [2].

Any HIL simulation involving power transfer to or from the hardware under test (HuT) is known as power hardware in the loop (PHIL). In this case, part of the power system is internally simulated and the other part is the actual power apparatus connected externally. A power source or sink (connected

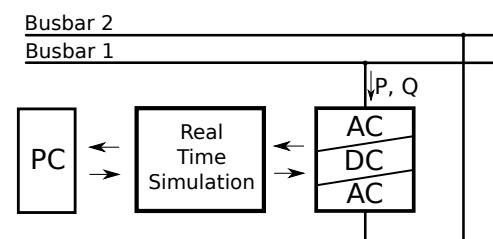


Fig. 1. General structure of Power HIL approach in load simulation

through the PHIL interface) is needed for this setup, which will either generate or absorb power (fig. 1). Reference signals are generated based on the solution of the virtual system inside the real-time simulator and are sent to the power amplifiers (PA) that produce voltages or currents to be applied to the HuT. Signals obtained from the ADC units of the HuT are scaled and feed in to the simulator to complete the simulation loop [1], [3].

Most common PA [4] units utilized in the PHIL are switch-mode type. Typical topologies include AC/DC/AC converter usually operating as a voltage or current source. Controller design, configuration of the filter and switching frequency depends on the PHIL application [3]. The latest trends in PHIL include applications able to mimic the dynamic behaviour of entire electrical networks, which may contain many generators, transmission lines, transformers and loads. Such an approach is called Network-In-The-Loop [5], [6]. This paper presents development of asynchronous machine model in agreement with the MIL and PHIL approaches. The model is developed in MATLAB Simulink environment based on approach presented in [7] and compiled to C language. Prepared model is then fed into the bidirectional ac/dc/ac converter (PA) driven by HIL simulator. Simulink xPC environment is used both to design the control algorithm and for the real time kernel running on the simulator.

The hardware and software infrastructure used in this research is a part of LINTE² laboratory. It is a research and development installation designed as a flexibly configured reduced-scale power system equipped with modern apparatus and power generating and converting units, as well as a powerful communication network. Flexible configuration of power circuits is achieved by a dedicated low-voltage switchgear

cabinet containing 9 AC buses, 1 DC bus, 426 contactors and circuit breakers remotely controlled via IEC 61850 protocol. The R&D installation includes units responsible for:

- autonomous power generation (a PV plant, 2 diesel generators, a gas microturbine)
- emulation of power sources (4 generating units driven by electric motors and emulating the properties of turbogenerators and wind generators)
- emulation of HV and MV transmission lines
- energy storage (stationary battery, flywheel, supercapacitors)
- FACTS (SVC, STATCOM, UPFC, HVDC)
- transformation of energy (multipurpose transformers with on-load power-electronic tap changers)
- charging of electric vehicles
- consumer loads (3 regenerative and 1 dissipative).

Each of those functional units/primary devices is governed by a functional unit controller (Target PC in terms of real-time simulation). The developed real-time algorithms can be accessed and revised for each of the controllers individually, by Simulink-Real-Time Explorer or thanks to SCADA control system. The functional unit in question (PA) is a 150 kVA regenerative consumer load. It consists of two AC/DC bi-directional converters with a DC link and a power-electronic 400/400 V transformer. The unit can consume or generate energy in terms of 3 work-modes: reference values of apparent power S ; active and reactive power P , Q ; or active and reactive current I . Figure 2 shows the unit representation in SCADA system.

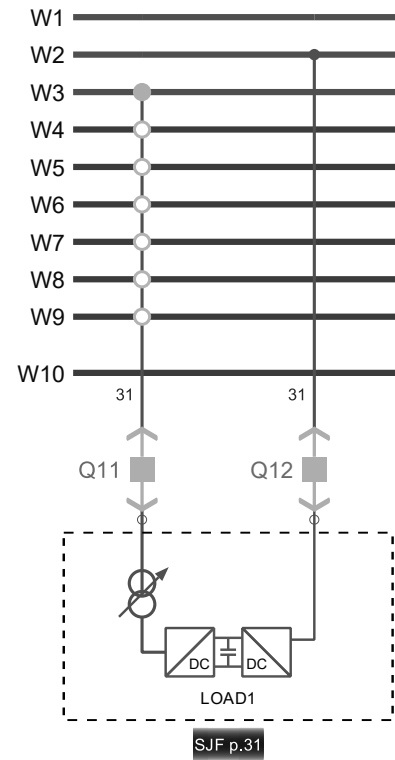
II. OBJECTIVES AND SCOPE

The aim of this paper, therefore, is to demonstrate the validity of PHIL approach in power system analysis and design based on a representation of machine behaviour in power system.

The rest of this paper is organized as follows. Section III offers the solution for the defined problem and highlights crucial aspects of asynchronous machine modelling. Section IV explains the implementation of the model in Simulink environment. Section V briefly presents the hardware setup used in this work and the results of simulations performed on the host PC and in the real time environment compared with experimental results of 5.5 kVA asynchronous motor Direct-On-Line starting. Section VI concludes on the validity of the proposed approach.

III. SOLUTION AND MODELLING

The proposed solution for the PHIL modelling of electromechanical converters is developed using an induction machine (IM) as example. Two models in Matlab Simulink are developed in order to compare the performance of both in proposed scenario. In the proposed scenario a Direct-On-Line (DOL) switching of large inertia induction motor is performed. The results of simulation using phasor model and $qd0$ arbitrary synchronous reference frame model of IM as well as the measurements on PA and real machine are compared. The PA



P	0.0 kW	P	-3.7 kW
Q	4.6 kvar	Q	3.4 kvar
S	5.1 kVA	S	4.8 kVA
IL1	7.0 A	IL1	8.1 A
IL2	7.3 A	IL2	8.4 A
IL3	7.3 A	IL3	8.1 A
UL12	406.0 V	UL12	405.8 V
UL23	404.5 V	UL23	402.7 V
UL31	405.4 V	UL31	406.1 V
cosφ	-0.186	cosφ	-0.595

Fig. 2. LINTE² laboratory LOAD1 functional unit

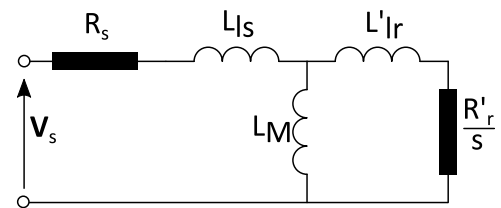


Fig. 3. Phasor model of IM - equivalent circuit

is controlled by the phasor model of IM. The general structure of IM model in $qd0$ arbitrary synchronous reference frame [8] in time domain is defined as:

$$\begin{aligned} \mathbf{v}_{qd0s} &= -\mathbf{R}_s \mathbf{i}_{qd0s} + \omega \lambda_{dq s} + \frac{d\lambda_{qd0s}}{dt} \\ \mathbf{v}'_{qd0r} &= \mathbf{R}'_r \mathbf{i}'_{qd0r} + (\omega - \omega_r) \lambda'_{dqr} + \frac{d\lambda'_{qd0r}}{dt} \end{aligned} \quad (1)$$

where \mathbf{v}_{qd0s} , \mathbf{v}'_{qd0r} are stator and rotor voltages in arbitrary synchronous reference frame, \mathbf{i}_{qd0s} and \mathbf{i}'_{qd0r} are stator and rotor currents, λ_{qd0s} , λ'_{qd0r} are stator and rotor flux linkages,

R_s, R'_r are stator and rotor winding resistances. The mechanical equation is defined as:

$$T_e = J \frac{1}{p} \frac{d\omega_r}{dt} + D\omega_r + T_L \quad (2)$$

where the electromagnetic torque, assuming the machine is magnetically linear, is the derivative of stored magnetic coenergy W_c over the rotor angular position:

$$T_e = p \frac{\partial W_c}{\partial \theta_r} \quad (3)$$

Equations 1, 2 and 3 define the behaviour of the machine during transient and steady state operation. In this analysis it is assumed that the stator and rotor voltages are balanced so that the zero component of $qd0$ model can be neglected. If we also assume that the q and d variables are sinusoidal in all but synchronous reference frames the steady state phasor voltage equations can be used to calculate machine currents:

$$\begin{aligned} \tilde{V}_s &= (R_s + jX_{ls})\tilde{I}_s + jX_M(\tilde{I}_s + \tilde{I}'_r) \\ 0 &= \left(\frac{R'_r}{s} + jX'_{lr}\right)\tilde{I}'_r + jX_M(\tilde{I}_s + \tilde{I}'_r) \end{aligned} \quad (4)$$

For steady state operation and simplified transient state performance the electromagnetic torque of the machine can be calculated from airgap power and synchronous rotational speed:

$$T_e = \frac{P_\psi}{\omega} \quad (5)$$

where the airgap power can be expressed as:

$$P_\psi = m \frac{R'_r}{s} |I'_r|^2 \quad (6)$$

In this simplified approach the machine is described using the impedance of machine equivalent circuit shown in fig. 3:

$$\tilde{Z} = R_s + jX_{ls} + \frac{jX_M \left(\frac{R'_r}{s} + jX_{lr}\right)}{\frac{R'_r}{s} + j(X_{lr} + X_M)} \quad (7)$$

and the stator and rotor currents are:

$$\begin{aligned} \tilde{I}_s &= \frac{\tilde{V}_s}{\tilde{Z}} \\ \tilde{I}'_r &= \frac{s\tilde{V}_s(-jX_{ls} - R_s + \tilde{Z})}{\tilde{Z}(R_r + jsX_{lr})} \end{aligned} \quad (8)$$

If we assume that $Im[\tilde{V}_s] = 0$ then the active and reactive current drawn by the machine from the grid is:

$$\begin{aligned} I_{active-Z} &= Re[\tilde{I}_s] \\ I_{reactive-Z} &= -Im[\tilde{I}_s] \end{aligned} \quad (9)$$

and the active and reactive power is:

$$\begin{aligned} P_Z &= mV_s I_{active-Z} \\ Q_Z &= mV_s I_{reactive-Z} \end{aligned} \quad (10)$$

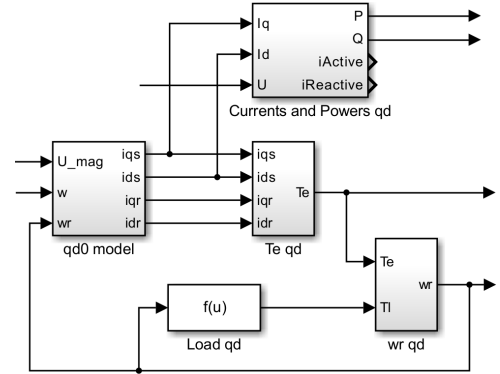


Fig. 4. General structure of $qd0$ model in MATLAB Simulink environment.

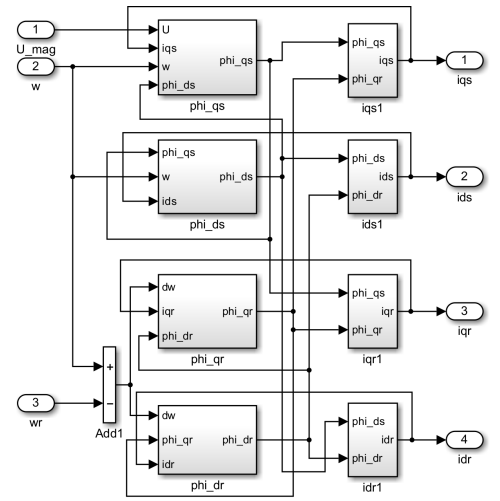


Fig. 5. Calculation of flux linkage and currents in $qd0$ model.

IV. IMPLEMENTATION

The $qd0$ MATLAB Simulink model is defined using integral form of the machine equations 1 and 2. Figure 4 shows general structure of the IM MATLAB Simulink model in arbitrary synchronous reference frame. The electromagnetic torque is calculated based on stator and rotor currents:

$$T_e = \frac{3}{2} p L_M (i_{qs} i'_{dr} - i_{ds} i'_{qr}) \quad (11)$$

The flux linkage (fig. 5) is calculated as:

$$\begin{aligned} \lambda_{qs} &= \int [\hat{V}_s - R_s i_{qs} - \omega \lambda_{ds}] dt \\ \lambda_{ds} &= \int [-R_s i_{ds} + \omega \lambda_{qs}] dt \\ \lambda'_{qr} &= \int [-R'_r i'_{qr} - (\omega - \omega_r) \lambda'_{dr}] dt \\ \lambda'_{dr} &= \int [-R'_r i'_{dr} + (\omega - \omega_r) \lambda'_{qr}] dt \end{aligned} \quad (12)$$

And the currents (fig. 5) are defined as:

$$\begin{aligned} i_{qs} &= \frac{\lambda_{qs} - i'_{qr} L_M}{L_{ls} + L_M} \\ i_{ds} &= \frac{\lambda_{ds} - i'_{dr} L_M}{L_{ls} + L_M} \\ i'_{qr} &= \frac{\lambda'_{qr} - i_{qs} L_M}{L'_{lr} + L_M} \\ i'_{dr} &= \frac{\lambda'_{dr} - i_{ds} L_M}{L'_{lr} + L_M} \end{aligned} \quad (13)$$

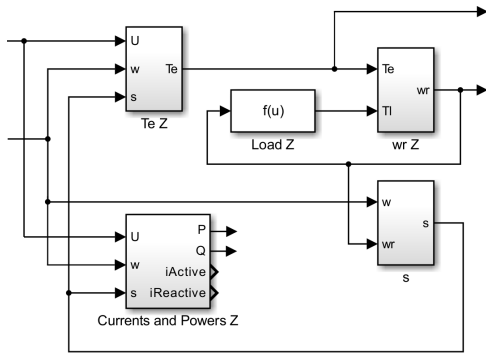


Fig. 6. General structure of phasor based model in MATLAB Simulink environment.

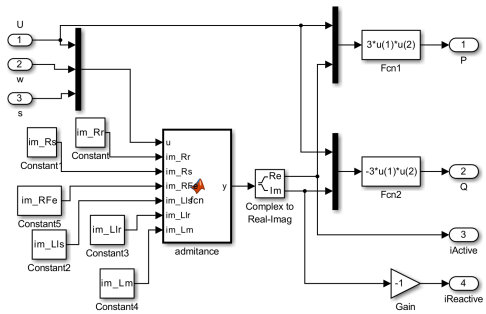


Fig. 7. Calculation of currents in phasor model.

and the active and reactive currents, assuming sinusoidal voltage and current waveforms, are:

$$\begin{aligned} I_{active-qd0} &= \frac{i_{qs}}{\sqrt{2}} \\ I_{reactive-qd0} &= \frac{2i_{ds}}{\sqrt{2}} \end{aligned} \quad (14)$$

and the active and reactive power is:

$$\begin{aligned} P_{qd0} &= mV_s I_{active-qd0} \\ Q_{qd0} &= mV_s I_{reactive-qd0} \end{aligned} \quad (15)$$

Figure 6 shows the implementation of phasor model formulated with relations 5 and 8. The active and reactive currents are calculated based on 9 and shown on fig. 7.

V. VALIDATION

Validation of the proposed approach was conducted using:

- Measurements of induction motor
- Simulations using $qd0$ model
- Simulations using phasor model
- Measurements of PA controlled by phasor model

The tests were conducted using $5.5kW$, $2925rpm@50Hz$ 1LA7130-2AA61 Siemens induction motor.

The measurements on real machine have been conducted with no load connected to the shaft. However additional inertia have been added to the machine by means of steel discs coupled to the machine shaft. The results of simulation and measurements are shown in fig. 8 and fig. 9. The active and reactive power represent the load of DOL starting of IM in the power system. In addition the simulation and measurements

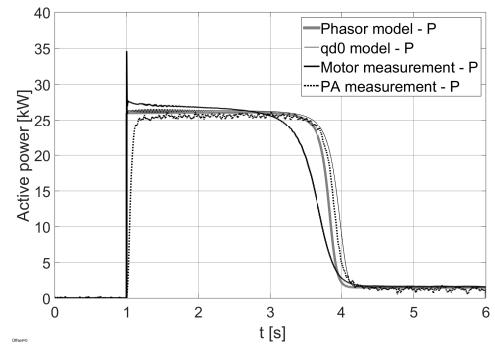


Fig. 8. Active power during DOL starting of IM - results of: measurements of real machine, measurements of PA controlled by phasor model, simulations using $qd0$ and phasor models.

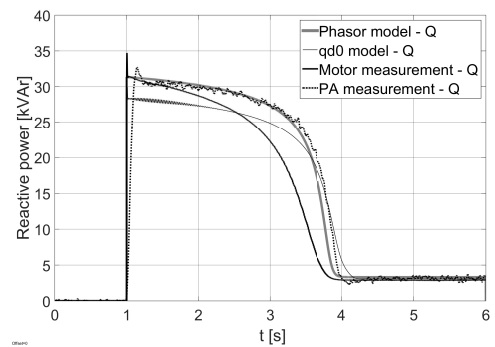


Fig. 9. Reactive power during DOL starting of IM - results of: measurements of real machine, measurements of PA controlled by phasor model, simulations using $qd0$ and phasor models.

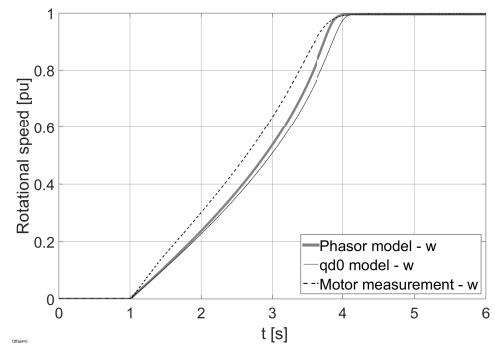


Fig. 10. Rotational speed during DOL starting of IM - results of: measurements of real machine and simulations using $qd0$ and phasor models.

results of rotational speed are presented in fig. 10 and the simulation results of electromagnetic torque are presented in fig. 11.

The results of tests conducted with real machine DOL starting compared with measurements give an indication that both proposed models perform satisfactorily, keeping in mind that the objective is the representation of IM load during the performance analysis of power system. Whether it will be on-grid operation or autonomous operation the phasor model performs as well as the $qd0$ model. It should be noted that the performance was tested using relatively high inertia machine

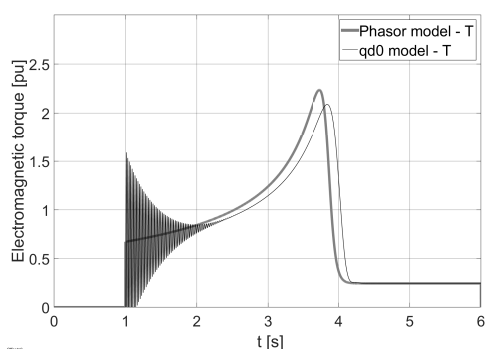


Fig. 11. Electromagnetic torque during DOL starting of IM - results of simulations using $qd0$ and phasor models.

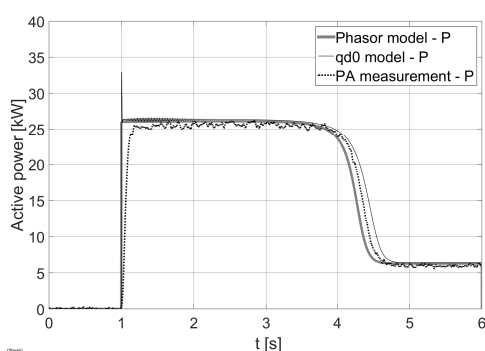


Fig. 12. Active power during DOL starting of IM - results of: measurements of real machine, measurements of PA controlled by phasor model, simulations using $qd0$ and phasor models.

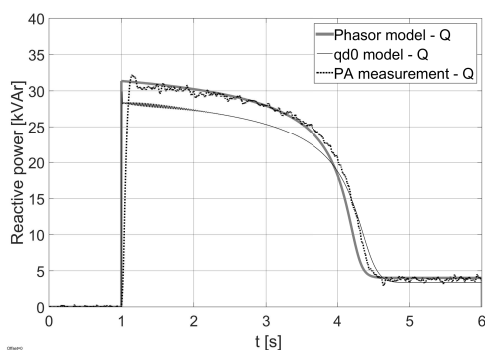


Fig. 13. Reactive power during DOL starting of IM - results of: measurements of real machine, measurements of PA controlled by phasor model, simulations using $qd0$ and phasor models.

and the results will be different for small inertia machines. Fig. 12 and 13 show the measurements of active and reactive power of PA controlled by phasor model load during DOL starting of IM with load.

VI. CONCLUSION

The objective of proposed approach is to develop control algorithm for PA. This Power-In-the-Loop approach allows for power system analysis using designed model of electromechanical converters to apply load to real components of the power system network. The advantages of real machine mod-

elling are especially important in autonomous power systems with large inertia IM, where the machine load can become a power source in case of system fault.

The high simplification level of proposed approach is adequate for proposed scenario of operation. By utilising proposed IM phasor model implementation the general behaviour of machine in power system is represented.

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