

Emulation of Mechanical Loads in Electric Drives – An Overview of Methods

Research paper

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Abstract: The aim of the presented paper is to introduce the reader to hardware-in-the-loop (HIL) simulation in electric drives, the motivation for its usage and its benefits. Basic information about HIL simulation in general and the connection to electric drives is followed by an explanation of the main principle of the dynamic emulation of mechanical loads for electric drives, which is a special case of HIL simulation. Next, the description of the three main methods of load emulation and their mathematical background are presented in the order of historical appearance: the emulation with compensator and tracking controller, the emulation based on non-linear control and the emulation with feed-forward compensation with the use of inverse dynamics.

Keywords: *electric drive • HIL simulation • load emulation*

1. Introduction to Hardware-in-the-Loop (HIL) Simulation

In the design and implementation of new technological devices and their control algorithms, testing and verification of their properties before deployment into the work process plays an important role (Bergmann, 2014). In the field of electric drives, this involves the testing of the complete drive: its control system, power converter and electric motor with driven mechanics. Testing and tuning of electric drives has several stages. Initial tests are mostly carried out using simulations with mathematical models in a simulation environment, for instance in MATLAB/Simulink. The main goal in this phase is to verify the applied methodology, its suitability for the assumed conditions and the principal functionality.

In the next phase, experiments with real devices should take place. Ideally, the experiments should be performed on a real system (real mechanics, production line, etc.). However, this is often impossible as it assumes performing the experiments at the customer site. Obviously, during the experiments, customer machines do not work. This leads to production shortage and undesirable expenses; therefore, customers are not inclined to allow experiments on a real production line or device. Therefore, there is an effort to minimise this idle time and perform as many tests as possible in the preparatory phase in a laboratory.

Low-power drives with simple mechanics can be tested in a laboratory without any problems. But more-complicated mechanics and high-power drives require expensive infrastructure that is not common in the laboratory. An especially problematic task is the replacement of the real mechanics or technology driven by the tested drive, which usually cannot be installed in a laboratory. Therefore, methods on how to carry out tests so that the drive control could be verified in the laboratory have been sought.

One of the methods that allow testing of such systems in a laboratory is HIL simulation. In HIL simulation, a part of the real device is replaced by its mathematical model that runs in real time on a special hardware (high-performance computer with special input–output interface). The main task of this equipment is to mimic the real machine with its physical inputs and outputs as well. Well-known representatives of HIL simulation hardware are

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products of dSPACE or OPAL-RT Technologies (e.g. HIL simulator OP5600 with the multi-domain Simulink-based software RT-LAB).

The HIL simulations of an electric drive can be divided into three basic levels (Bouscayrol, 2008):

- process control level;
- power electronics level;
- mechanical level (including electric motor).

For each level, a different number and type of hardware (HW) devices involved in HIL simulation are used. The first step in HIL simulation is to build a mathematical/simulation model of the entire tested system with all components. To speed up the simulation, some parts of the system can be simplified.

1.1. HIL on process control level

In the first level, only a control unit (CU), computer or device, whose task is to control the process, is involved in the experiments. Other components of the system, such as power converter, electric motor and mechanical parts, are simulated in real time using appropriate HIL software (SW) and HW (Figure 1). The simulation system manages inputs and outputs to and from the CU in the same way as in a real system. The interface between the tested CU and the simulation system is operated by control signals only.

If the HIL is applied on process control level for electric drives, it is necessary to use simulation HW with sufficient computing power and fast communication speed between simulation HW and CU. The reason is the need for power converter simulation with fast transients. In order to achieve satisfactory simulation results, it is necessary that the sampling frequencies of the simulation HW are at least 10 times higher than the sampling frequency of the tested CU.

Although simulation on the process control level in electric drives is possible, simulation on this level is mainly used in the design of electronic CUs (ECUs) for vehicles. The vehicle mechanics (or component) is replaced by a mathematical model running on simulation HW that generates for ECU the same signals as the ECU in a real vehicle gets from sensors. The ECU then sends control commands back to the model on simulation HW.

1.2. HIL on power electronics level

In the level of power electronic simulation, the real power converter with its CU is used. The remaining part of the system, for instance an electric motor with mechanical load, is simulated in real time on simulation HW (Figure 2).

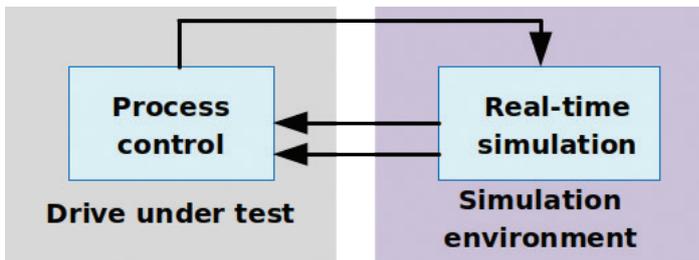


Fig. 1. HIL on process control level—block diagram. HIL, hardware in the loop.

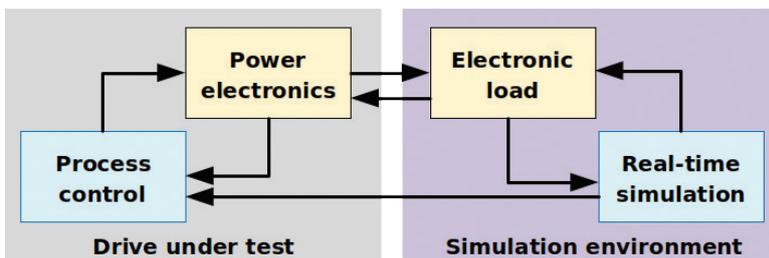


Fig. 2. HIL on power electronics level. HIL, hardware in the loop.

In comparison to process control level, the simulation HW includes also a programmable electronic load. The control of electronic load must enable an emulation of an electric motor that will be used in the real system, including a driven mechanics. At the same time, the load must be able to dissipate the full power of the power converter, which can be a real problem at higher powers. In addition, when required to test the drive during reversing, the electronic load must allow bi-directional power flow.

1.3. HIL on level of mechanics

To thoroughly verify the drive functionality, it is necessary to test the drive with the mechanical load that will be present in real conditions. Since the real mechanical load is often either unavailable (i.e. requires production line shutdown) or cannot be tested in laboratory conditions, various types of control algorithms have been developed for drive-testing purposes. The task of these control algorithms is to simulate the load that would act on the drive shaft in real operation. During testing, the impact of this load on the entire drive technology is investigated.

One of the options for mimicking the mechanical loads is deploying another electric drive, as shown in Figures 3 and 4, where the tested drive is called the drive under test (DUT) and the loading drive is called the loading machine (LM). If the electric drive operates with constant torque, a simple dynamometer can be used as the LM (Wasko, 1987; Williamson, 1989). Here, the LM operates in the torque control mode, working as a generator. If the emulation of variable load torque is required, the torque of the LM needs to be manipulated according to a working cycle, where the working cycle can be defined by its parameters, for example by dependence of the load torque on time, speed or position. If we want to emulate the moment of inertia and possibly its change as well, a dynamic torque must be added to the load torque.

The parameters mainly monitored to verify the accuracy of the emulated load against the real one are the mechanical values on the shaft, such as position, angular velocity and torque. If these emulated quantities match the quantities on the real drive, we can conclude that the emulation is correct and the drive is ready for testing. It is important to note that such tests do not verify the influence of environmental properties such as humidity, environmental temperature, radiation or external vibrations.

In a simpler way, the load torque is controlled in an open loop, where the torque setpoints are defined in terms of dependence on time by the user (Collins and Huang, 1994; Newton et al., 1995; Sandholdt et al., 1996). Such an approach is used if a real device is available, but the design of the mathematical model of a driven load is too complicated. In this case, mostly, only a duty cycle in the form of a dataset of the measured variables is available, that is, the actual position and torque are recorded during the whole duty cycle at the given sampling rate. Next, the measured load torque is used as the torque setpoint for the LM in the emulation. The torque setpoint can be entered in terms of dependence on time or measured speed and/or an actual position. In a previous paper (Šlapák et al., 2021), a load emulation based on such an approach with an experimental dataset and industrial equipment is described. The main advantage of the described method is

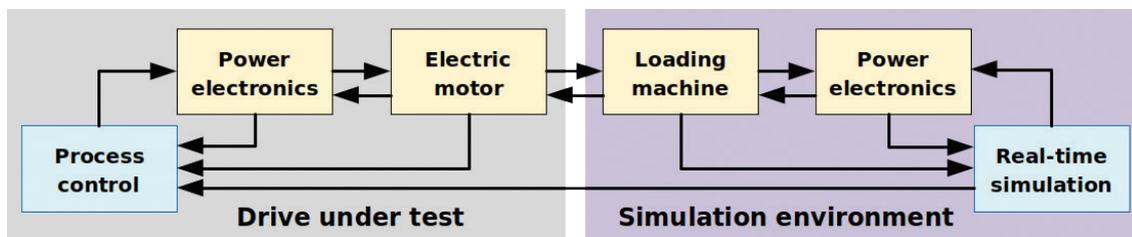


Fig. 3. HIL on level of mechanics. HIL, hardware in the loop.

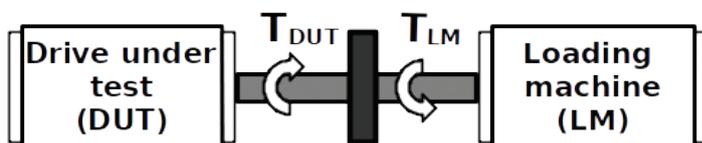


Fig. 4. The mechanical setup of HIL on level of mechanics. DUT, drive under test; HIL, hardware in the loop; LM, loading machine.

the quick implementation of various datasets. The main disadvantage is the need for measured values from a real system, which may be unavailable during the development process. Furthermore, it is problematic to build up a new scenario (e.g. with a different movement of the robotic arm) as it requires new measurements on the real system.

Therefore, it is more advantageous if a mathematical model of the mechanical load is available. In such a case, prescribing the motion profile is much more convenient, as no measurements on the real system are needed. The advantage is also the accuracy of the emulation in comparison to the previous method as it is not affected by the accuracy of the available samples. However, the main advantage of emulation with a mathematical model is that it is possible to prepare the emulation even when the real mechanics is not yet available, for example is not manufactured or when the real system is not free for experiments. Especially, if a new algorithm for an electric drive is being developed for an existing production line or its components, it is not possible to stop the production whenever new measurements are required.

Moreover, if a control algorithm for industrial application with deployment of a commercial power converter is developed, the set on Figure 4 allows us to build the DUT on the same platform as it will be used later at the production site. It is important to note that industrial power converters have the same control SW for the entire power range. This allows testing of the control algorithm for a high-power drive on the same type of power converter with significantly less power in a laboratory. This eliminates the need for high-power sources and loads for testing in the laboratory. Another advantage is that the control algorithm is developed and tested on the final platform with all its possibilities and limitations. The debugged algorithm can thus be directly transferred to the power converter on site, and it is not necessary to rewrite it to another platform and re-debug it again. Such a procedure significantly reduces the time that is required to drive commissioning in the factory. Such an approach was used in the design of a vertical iron scale breaker control in a hot rolling mill. The control of two 1.1 MW drives with torque balancing was tested in the laboratory on a drive with a power of 13 kW (Fetyko et al., 2007).

If a control algorithm is being developed for an industrial drive, it is advantageous if the HIL system and the power converters are mutually compatible. This simplifies and speeds up data transfer between the control system and power converters. Another advantage is if the control system and converters enable so-called 'task synchronous operation'. This functionality eliminates delays in data transfer between devices. Such properties are offered by, for instance, the SIMOTION control system, in combination with power converters of the SINAMICS S120 family, from Siemens Company.

Nowadays, the research in the field of load emulation is focussed on dynamic emulation, which enables to emulate mechanical loads with fast transient events (e.g. rotary shear, elastic shaft) or systems with non-linearities (e.g. drives with gearboxes). Next, the research also focusses on applications in electric drive development and test processes, for example:

- backlash emulation (Kyslan et al., 2014);
- emulation of wind turbines (Damian et al., 2019; Rojas et al., 2019);
- emulation of loads for vehicle systems (Rodic et al., 2007; Zhang et al., 2017).

In this article, the overview of various methods for dynamic emulation of mechanical loads is presented. First, the main idea behind the emulation methods is introduced. Next, the three main methods are described with the overview of their further investigation and applications. Finally, the deployment of the dynamic emulation method on a simple pendulum is demonstrated.

2. Basic Principle of Dynamic Emulation of Mechanical Loads

In the real system, the electric drive is attached to the real mechanics. In general, the relationship between angular speed and torque for such an electric drive can be described by the well-known mechanical equation for electric drives:

$$\frac{d\omega}{dt} = \frac{1}{J(\omega, \varphi)} [T_{DUT} - T_{fr}(\omega) - T_{add}], \quad (1)$$

where $J(\omega, \varphi)$ is the overall inertia, T_{fr} is the viscous friction and T_{add} is the additional load, which is unknown. If the unknown additional torque is considered as part of the friction, then Eq. (1) can be rewritten as follows:

$$\frac{\omega(s)}{T_{DUT}(s)} = G_{RM}(s) = \frac{1}{J(\omega, \varphi)s + B}, \quad (2)$$

where $G_{RM}(s)$ is the transfer function of the real mechanics.

Let us consider the situation where no mechanics but another electric drive is present, which should behave as a load (Figure 4). The speed–torque relationship of such a test rig can be expressed as follows:

$$\frac{\omega(s)}{T_{DUT}(s)} = G(s), \quad (3)$$

where $G(s)$ is the dynamics of the rest of the test rig, which obviously differs from the dynamics of real mechanical HW.

Now, the aim of emulation is to find a way to manipulate the LM torque to achieve the same effect from the DUT point of view, as with the real mechanics, that is, the transfer function of the system with emulation $G(s)$ should be equal to the transfer function of the real mechanical system, $G_{RM}(s)$.

In the emulation, the DUT can operate either in position or speed control mode exactly as in a real system, whereas the LM is operating in a torque control loop. The control algorithm calculates the reference, that is, torque setpoint T_{Lr} , for the LM. The input variables of the algorithm are the torque setpoint for DUT T_{DUTr} (output of speed controller) and actual angular velocity ω or shaft position of drive φ , depending on the selected control structure. The universal scheme valid for most types of dynamic emulations is shown in Figure 5.

In some methods, instead of the torque setpoint T_{DUTr} generated by the speed controller, the torque setpoint \hat{T}_{DUTr} got from the observer is used. The observer calculates this value from the DUT currents and the actual angular velocity of the emulated mechanical system.

In the following sections, the three methods of LM control are presented.

3. Emulation Method with Compensator and Tracking Controller

A method using an analytical compensator has been described previously (Akpolat et al., 1999a, 1999b; Gan et al., 2015). The aim of the compensator is to compensate the dynamics of the whole mechanics except the emulated one. The principal control structure of the method is in Figure 6, where $G(s)$ is the transfer function of the test rig dynamics, $G_{comp}(s)$ represents the compensator, $G_t(s)$ is the tracking controller and $G_{em}(s)$ is the transfer function of the emulated load.

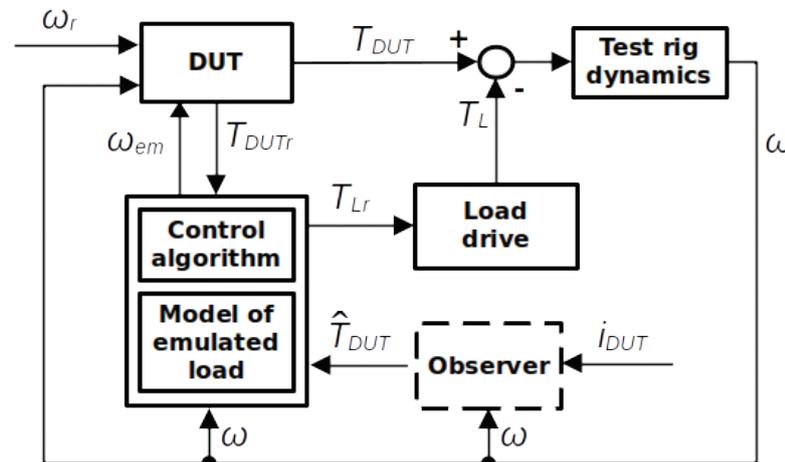


Fig. 5. The basic structure of dynamic emulation of mechanical loads. DUT, drive under test; em, emulation.

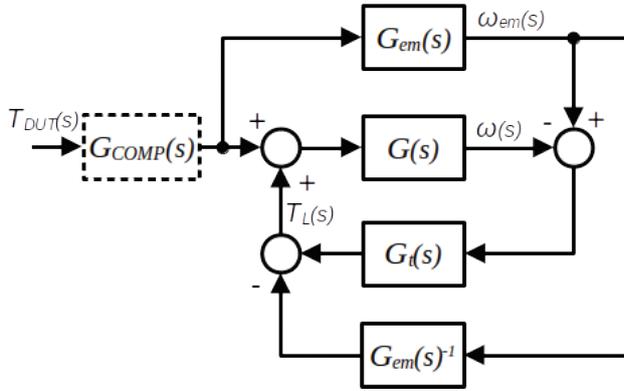


Fig. 6. Principal control structure of the emulation method with the compensator and tracking controller. COMP, compensator; DUT, drive under test; em, emulation.

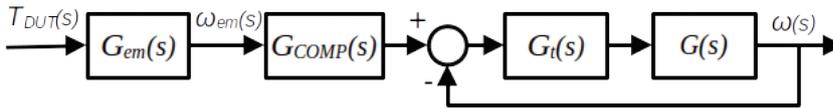


Fig. 7. Simplified control structure for emulator with compensator. COMP, compensator; DUT, drive under test; em, emulation.

The transfer function of the system dynamics for the described structure, without a compensator, would be as follows:

$$\frac{\omega(s)}{T_{DUT}(s)} = G_{em}(s) \frac{G(s)G_t(s)}{1 + G(s)G_t(s)} = G_{em}(s)G_{COMP}^{-1}(s), \quad (4)$$

where the equation for the compensator is

$$G_{COMP}(s) = \frac{1 + G(s)G_t(s)}{G(s)G_t(s)}. \quad (5)$$

Next, if this compensator is incorporated into the system, the transfer function is

$$\frac{\omega(s)}{T_{DUT}(s)} = G_{em}(s), \quad (6)$$

which means that the relationship between the torque and speed is dependent only on the emulated load. Using the mathematical description, the principal control structure of the emulator with compensator can be simplified as depicted in Figure 7.

The emulation method with compensator and tracking controller allows us to emulate both linear and non-linear mechanical loads without the need for an inverse model of mechanical dynamics. However, the compensator contains the transfer function of the tracking controller, which causes a delay in load emulation in comparison to the ideal load.

The described method was also implemented in position-controlled system using position tracking (Akpolat et al., 2004; Arellano-Padilla et al., 2006). The experimental rig consisted of two 0.55 kW electric motors and the sampling time for emulation was set to 2.5 ms.

4. Emulation Method Based on Non-Linear Control

The method improves the emulation with compensator by generalising the dynamics of the DUT-LM mechanism (Rodič et al., 2004–2010). Here, the system of the test rig can be split into linear parts (moment of inertia and

viscous friction) and possible non-linearities, represented by the additive load T_{ad} , which may, for example depend on the direction of rotation (Figure 8).

Although the actual value of these non-linearities is not known in most cases, the main aim is to eliminate non-linearities by proportional–integral (PI) controller or PI estimator in the compensator $G_{COMP}(s)$.

The emulated load (denoted as G_{em}) is depicted in Figure 9. As can be seen, the acceleration has been added to the outputs of the block. The block B_{em} represents the friction of the emulated load. The outputs of block G_{em} are the angular velocity and the angular acceleration (Figure 10).

A control scheme with the PI estimator is shown in Figure 9. The acceleration output of block G_{em} is corrected by the tracking controller G_t with gain k , which compensates the numerical errors and parameter uncertainties. The corrected value then enters the compensation part G_{COMP} .

Based on Figures 8 and 9, we can write

$$T_{DUT} - T_L = J \frac{d\omega}{dt} + B\omega + T_{ad} . \tag{7}$$

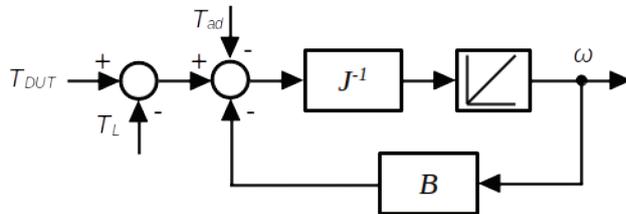


Fig. 8. Dynamics of test rig mechanics, block G. DUT, drive under test.

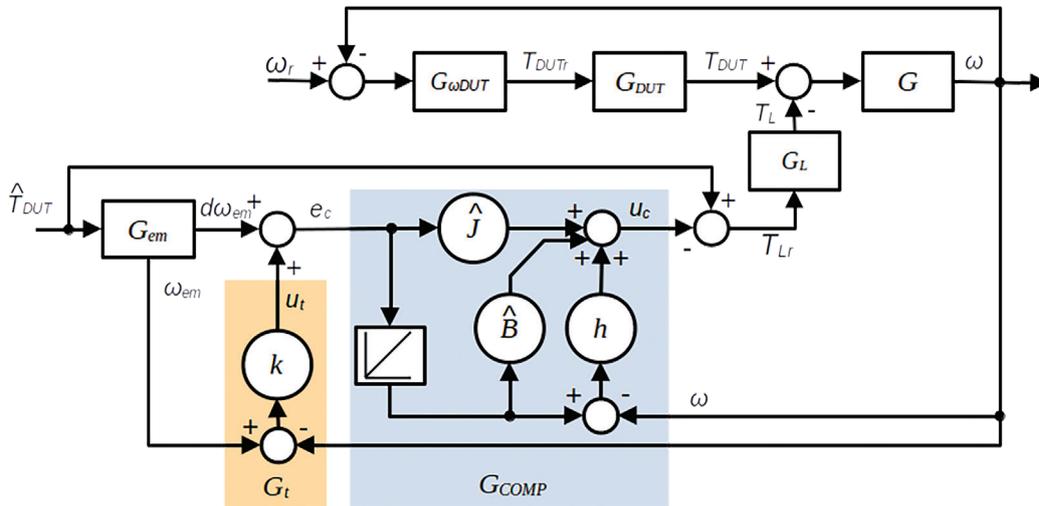


Fig. 9. Emulation control scheme with the PI estimator. COMP, compensator; DUT, drive under test; em, emulation; PI, proportional–integral.

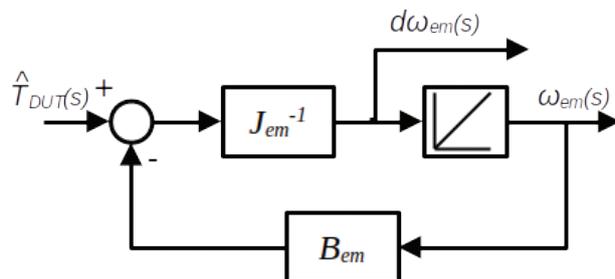


Fig. 10. Emulated load, block G_{em} , DUT, drive under test; em, emulation.

Assuming ideal dynamics of LM ($G_L(s) = 1$), from Figure 9, it follows that

$$T_L = \hat{T}_{DUT} - u_c. \quad (8)$$

If we substitute Eq. (8) into Eq. (7) and assume ideal estimation of the DUT torque ($T_L = \hat{T}_{DUT}$), Eq. (7) becomes

$$J \frac{d\omega}{dt} + B\omega + T_{ad} = u_c. \quad (9)$$

The output of the compensator, u_c , compensates the emulator dynamics G . The compensator is an inverse model of emulator dynamics, which includes the calculated or measured inertia \hat{J} and coefficient of viscous friction \hat{B} . Further, the compensator includes a PI estimator with the gain h , which compensates the unknown non-linear load T_{ad} . For the compensator output u_c , the following applies:

$$u_c(s) = \left(\hat{J} + \frac{\hat{B} + h}{s} \right) e_c(s) - h\omega(s), \quad (10)$$

where

$$e_c(s) = d\omega_{em}(s) + k(\omega_{em} - \omega) = \varepsilon_{em}(s) + k(\omega_{em} - \omega). \quad (11)$$

Assuming a precise emulator model, in Eq. (11), the input to the compensator e_c would be directly equal to the emulated acceleration ε_{em} (without correction of tracking controller G_τ). Since such a state cannot be achieved, the feedback controller G_τ with gain k and output u_τ is used in the control structure, whose task is to compensate for possible numerical errors and parameter changes.

The described method is suitable for emulation of both linear and non-linear loads and in position-controlled drives (Rodič et al., 2010). The method's disadvantage lies in the possibility of introducing errors by inaccurate system parameter identification, which can limit the operation bandwidth (Rodič et al., 2010). The method has been further investigated and implemented into industrial power converters using the Drive Control Chart programming tool (Suchý et al., 2016).

5. Emulation Method with Feed-Forward Compensation

The emulation method presented by Oliveira et al. (2020) considers emulator model uncertainties $\Delta G(s)$ and application of inverse emulator dynamics as feed-forward compensation (Figure 11). The output of the compensator

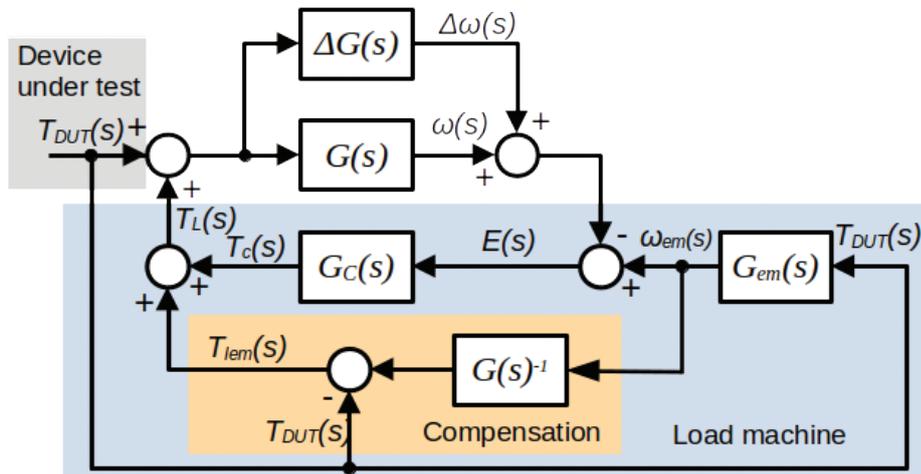


Fig. 11. Load emulation with feed-forward compensation. COMP compensator; DUT, drive under test; em, emulation.

is the part of LM reference, denoted as $T_{lem}(s)$. The second part of the reference is given by the tracking controller $G_c(s)$.

The system dynamics is

$$\frac{\omega_m(s)}{T_{el}(s)} = G_{em}(s) \left[\frac{1 + \Delta G(s) + G_c(s)G(s)\Delta G(s) + G_c(s)G(s)}{1 + G_c(s)G(s)\Delta G(s) + G_c(s)G(s)} \right] = G_{em}(s)G_{equ}(s). \quad (12)$$

Again, exact emulation is achieved if $G_{equ}(s) = 1$. The advantage of this approach, comparing to a previous work (Gan et al., 2015), is the independence of the emulation model from the system bandwidth, as no G_{em} is presented in G_{equ} . Moreover, in comparison to the previous method, no acceleration output from the emulated load is needed. The disadvantage is the need of inverse system dynamics in the control structure.

The described method was experimentally verified by the authors (Oliveira et al., 2020) using two induction machines and the state observer of the shaft torque to resolve implementation issues, usually linked with the compensator with filter. The control algorithm was programmed into floating point digital signal controller, which controlled two commercial inverters on the same DC link.

6. Simulation Results

A demonstration of the emulation method based on non-linear control was performed to describe the load emulation principle and to show the basic functionality. A simple pendulum (Figure 12) was selected as an example.

A dynamic model of the pendulum is described by the following equations:

$$\frac{d\omega_{em}}{dt} = \frac{1}{J_{em}}T_{DUT} - \frac{1}{J_{em}}mgl \sin(\phi_{em}) - \frac{1}{J_{em}}B_{em}\omega_{em}, \quad (13)$$

$$\frac{d\phi_{em}}{dt} = \omega_{em}, \quad (14)$$

where g is the gravitational acceleration and ϕ_{em} is the angular position of the pendulum arm. The pendulum with weight $m = 1.5$ kg is placed at the end of the arm with length $l = 0.21$ m. A continuous movement in one direction

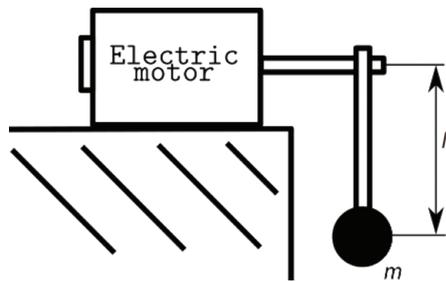


Fig. 12. A simple pendulum—emulated load.

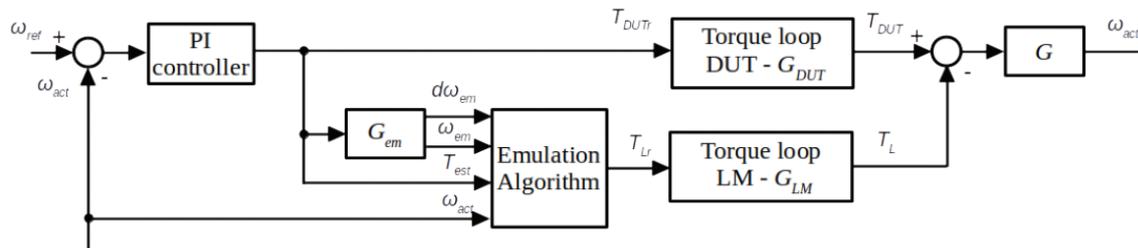


Fig. 13. Simulation scheme. COMP, compensator; DUT, drive under test; em, emulation; LM, loading machine; PI, proportional–integral.

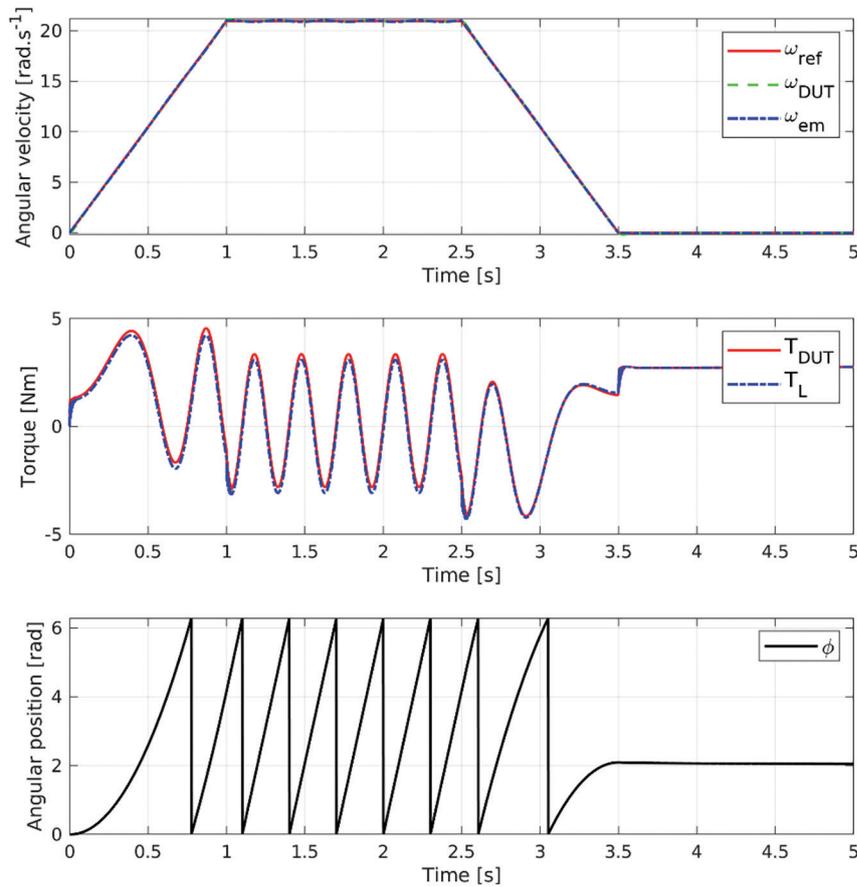


Fig. 14. Simulation results—A simulation of simple pendulum load emulation using a method based on non-linear control. DUT, drive under test; em, emulation; ref, reference.

was simulated. The movement starts at zero angular position (bottom position). At the end of the movement, the load stays in a non-zero angular position. A drive must generate a non-zero torque to maintain this position. The simulation scheme of the system is shown in Figure 13, and the simulation results are in Figure 14.

The simulation results clearly show the behaviour of a pendulum in a gravitational field. In the upper plot, the motion profile of angular speed is shown. The emulated speed follows the speed of DUT (actual speed). In the middle plot, a comparison of the machine torque T_{DUT} and the emulated load torque T_{LOAD} can be seen. The difference in both waveforms is caused by the viscous friction, which was considered in the simulation as well. The emulated load torque is the torque setpoint for the LM. The last plot documents the angular position of the pendulum arm.

In the time from 2.5 s to 3.5 s, the load helps to slow down the system; hence, a lower torque is present. At the time point of 3.5 s, the movement stopped with the arm in the position of approx. 110° (i.e. almost horizontal position); thus, the load and machine torque remained high.

7. Conclusion

In the paper, an overview of the methods used for the dynamic emulation of a mechanical load has been presented. The main principle has been described, along with three different approaches. Although the methods using an open loop control structure are very simple, they can still find their application in industrial practice, for example in verifying the drive's thermal performance. Anyway, the closed-loop methods are more versatile. They enable the user to perform drive testing with various loads and work cycles, which are very close to the behaviour of the

real mechanical system. Using load emulation, a very high level of drive system preparation can be done before implementing the drive into a real system, thus significantly shortening the time needed for commissioning.

The simulation results presented in this paper show the principle and basic functionality of dynamic emulation of mechanical loads. The experimental results can be found in the mentioned literature, where the described methods were experimentally verified by their authors using high-performance computing equipment. The practical implementation of these methods into industrial control systems, as were described in the literature, proved their potential in industrial practice as well. However, the full performance and accuracy of the emulation methods depend on the availability of mathematical models of the real systems.

The new challenges in load emulation are to properly emulate the load of more-complex drives, especially drives with fast changes of load torque, such as elastic shafts or rotary shears for metal sheet cutting. Another interesting area is the emulation of drives with gearboxes, where the non-linear behaviour of gearbox efficiency is involved. These are the fields of further research.

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