Mechanical drive train emulation by means of electrical drives - a generalised approach

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Abstract—The emulation of mechanical systems by means of electrical systems is an application of electrical machines and drives which have received increased attention in the recent years. As power electronics-controlled machines are dynamically faster than conventional mechanical systems, it is widely recognised that the behaviour of the latter can be emulated by a proper electrical machine torque control. Different test benches with different emulation capabilities have been proposed in the literature, but few attention has been posed to two aspects: the requirements of the drive emulator in terms of rated torque and/or power and/or bandwidth, and the emulation of effects like mechanical resonances within test benches with rigid mechanical connection. The paper tries to focus on these two aspects with both simulation and experimental results, in order to depict a general approach to the design of a drive emulator.

Index Terms—Motor drives and electrical machines, drive applications, new implementation approaches.

I. INTRODUCTION

As electrical machines controlled by power electronics converters have reached the stage of robust, mature and dynamically fast products, the emulation of mechanical systems by means of electrical drives arise as a new research topic. In some cases, the development of test benches based on electrical drives instead of real mechanical systems is justified in terms of cost and flexibility of the bench itself. As for the first aspect, an electrical drive emulator can be sensibly cheaper than a complex system with different mechanisms. As for the second aspect, a single drive emulator can be programmed to reproduce the static and dynamic behaviour of different mechanical systems (when the rated power is sufficient), providing a large freedom to test different cases and different mechanical parameters at once.

As a branch of the research in the electrical drive scenario, the emulation of mechanical systems has been primarily driven in the past by traction. In such systems, emulation has been employed to replicate the behaviour of combustion engines [1], electrical steering systems [2] or more recently steer-by-wire systems [3] and gas engine start-up sequences for all-electric vehicles with embedded generators [4]. Nevertheless, drive train emulation has been also employed in the renewable field, as in the wind energy scenario, where different Authors proposed wind turbine test benches reproducing the dynamics of a real turbine on a smaller scale. Examples of induction machines emulating wind turbines are found in [5] and [6].

An interesting work is [7], where an attempt to emulate non-linear periodic effects in a wind turbine has been performed.

Recently, the need of a more systematic approach for the design of a drive emulator has increased. An example is represented by [8], which documents an approach for the virtual load emulation of a vehicle dynamics, including the mechanical connection of the ball-screw system that steers the wheels. The vehicle model is a simplified non-linear system, while the mechanical connection is a linear system. Although some hints regarding the tuning of the regulators for the drive emulator are given, no general approach is obtained and no considerations are given regarding the rating of the motor and the converter for the drive emulation.

An interesting work has been presented in [9]. The paper describes a model-based control method for a synchronous motor, which emulates the behaviour of a twin-shaft gas turbine engine as it drives an electric generator supplying power to steady-state and dynamic loads. The approach is more detailed with respect to the previous works in the literature. Some tuning aspect for the emulator controller are discussed, but no considerations are given regarding the presence of resonances, while the rating of the emulator is indirectly discussed when considering different inertia values.

This paper proposes a more general approach for the implementation of a drive emulator, by considering the basic cases (passive loads or active loads) and the implications of using an electrical drive instead of the real mechanical system. Focus will be given to the emulation of mechanical characteristics that are not present in the mechanical setup of the test-bench, such as resonances. Considerations regarding the tuning of the controller, the rating of the machine/drive for the emulator and the bandwidth of the system will be discussed. Simulation results on an active load case are performed and reported in Sect. III, while experimental results are included in Sect. IV. Some remarks will conclude the paper in Sect. V.

II. GENERALISED MODEL EMULATION

A general approach for the requirements of an electrical drive which should emulate a generic mechanical model must consider different aspects. A first important step is the definition of the load type, which could be passive or active. In the passive load case, a mover (usually an inverter-fed electrical machine) is connected to a mechanical load which acts as

an inertia, with the possible intervention of mechanical resonances and/or friction of different nature (stiction, viscosity). The passive load may also be non-linear (pump cavitation, for example). The task of the electrical drive emulator is to reproduce mechanical characteristics which are not evident in the laboratory test-bench mechanical connection, as for example the reproduction of resonances on a rigid shaft.

In the active load case, the mover is connected to a second mover through mechanical means, which could contain resonances and frictions as in the passive load case. In this situation, the second mover actively contributes to the torque production in a linear or non-linear way. Such situation is very common in all type of generation installations (wind, hydro, gas turbines coupled with generators). In such a case, the drive emulator should take care of both the behaviour of the second mover (i.e. the turbine) and the reproduction of mechanical characteristics that are not present in the laboratory test bench.

The definition of the load type has a direct relation to the torque and power requirements of the drive emulator, but a correct selection of the rating does not imply a correct emulation of the load, which is heavily dependent on the control design. In the following sections, the two load types (passive and active) will be analysed in detail. Control aspects as well as rating requirements will be given in both cases.

A. Case 1: passive load

A block diagram that describes a general connection scheme between the mover and a second electrical drive that should reproduce the passive load is reported in Fig. 1. The elements inside the dashed box represent the electrical drive emulator.

Fig. 1. Block diagram of a passive load emulation with an electrical drive.

Each block is named with its corresponding transfer function in the Laplace domain. A torque reference τ_1^* is generated by a control algorithm and sent to the torque control loop C_1 of the drive that controls the mover. The resulting generated torque τ_1 , along with the torque τ_2 whose nature will be soon analysed, contributes to the dynamics of the mechanical speed ω_m through the mechanical model M . It is worth to underline that M is the model of the actual mechanical connection of the laboratory test-bench, which could be a simple stiff shaft.

The dynamics of ω_m is compared to the dynamics of an emulated mechanical speed $\omega_{m,em}$, which is the output of a desired mechanical model M_{em} implemented in a microprocessor or FPGA. The model M_{em} is fed by the same torque

reference τ_1^* . In order to take into account the dynamics of the torque control loop, C_1 (or a valid approximation of it) should be inserted in the control chain of the emulated model, as shown in the dashed box of Fig. 1.

The difference between the emulated and actual speed is processed by a regulator R_{em} , whose output is a torque reference τ_{em}^* for the electrical drive emulator. The torque control loop of the drive emulator has a dynamics represented by C_2 , as in Fig. 1. The actual torque τ_2 is added to τ_1 in order to modify the characteristics of M in real time.

The requirements for the electrical drive emulator are obtained through an analysis of the transfer functions of the diagram in Fig. 1. The relation between the mechanical speed and the torque references is given by the following expression:

$$\begin{aligned}\omega_m &= M\tau \\ &= M(\tau_1 + \tau_2) \\ &= M(C_1\tau_1^* + C_2\tau_{em}^*)\end{aligned}\quad (1)$$

By substituting τ_{em}^* with the blocks contained in the dashed box of Fig. 1, the following expressions occur:

$$\begin{aligned}\omega_m &= M[C_1\tau_1^* + C_2R_{em}(\omega_{m,em} - \omega_m)] \\ &= M[C_1\tau_1^* + C_2R_{em}(M_{em}C_1\tau_1^* - \omega_m)] \\ &= M[C_1(1 + C_2R_{em}M_{em})\tau_1^* - C_2R_{em}\omega_m]\end{aligned}\quad (2)$$

By grouping the mechanical speed on the left side of the equation, it follows:

$$\omega_m(1 + MC_2R_{em}) = MC_1(1 + C_2R_{em}M_{em})\tau_1^* \quad (3)$$

from which it is easy possible to calculate the transfer function from τ_1^* to ω_m :

$$\frac{\omega_m}{\tau_1^*} = \frac{MC_1(1 + C_2R_{em}M_{em})}{1 + MC_2R_{em}} \quad (4)$$

By considering that $\tau_1 = C_1\tau_1^*$, the mechanical load transfer function is obtained:

$$\frac{\omega_m}{\tau_1} = \frac{M(1 + C_2R_{em}M_{em})}{1 + MC_2R_{em}} \quad (5)$$

Expression (5) is worth analysing, since both the actual mechanical model and the desired (emulated) mechanical model appear in the equation. A degree of freedom is represented by the presence of the regulator transfer function R_{em} . If a proper emulation of the model M_{em} is required, R_{em} must be shaped accordingly. In the case of the passive load, the following relation occurs:

$$\begin{aligned}\frac{\omega_m}{\tau_1} &\cong M_{em} \\ &\text{for } M_{em}C_2R_{em} \gg 1 \text{ and } MC_2R_{em} \gg 1\end{aligned}\quad (6)$$

which means that the regulator should be designed taking into account the characteristics of the both M_{em} and M . A consequence of the (6) is that the conditions may be fulfilled only for a limited bandwidth, which must be kept in mind when selecting the desired mechanical model to emulate.

Some considerations can be made as regards to the ratings of the electrical machine coupled to the drive emulator. By analysing Fig. 1, the maximum emulated torque reference

is obtained for maximum values of the speed difference multiplied by the transfer function of the regulator:

$$\begin{aligned}\tau_{em,max}^* &= \max |R_{em} \Delta \omega_m| \\ \tau_{em,max}^* &= \max |R_{em} (M_{em} - M)| \cdot C_1 \tau_1^* \quad (7)\end{aligned}$$

Consequently, the ratio between the emulated torque reference and the torque reference generated by the main electrical drive is given by:

$$\frac{\tau_{em,max}^*}{\tau_1^*} = \max |R_{em} (M_{em} - M)| C_1 \quad (8)$$

By considering that usually torque control loops perform a fast tracking of the torque references with no gain loss and larger bandwidth compared to the mechanical dynamics, the transfer function C_1 can be neglected:

$$\frac{\tau_{em,max}^*}{\tau_1^*} \cong \max |R_{em} (M_{em} - M)| \quad (9)$$

The expression (9) can be easily used to determine the torque rating of the electrical machine connected to the drive emulator.

B. Case 2: active load

The second case under analysis is represented by two movers (usually an electrical machine and a prime mover, as for example a turbine), connected together by means of a mechanical drive train. Each of the mover actively contributes to the dynamics of the mechanical speed.

Fig. 2 reports a general block diagram of an active load emulation performed through an electrical drive, which is enclosed in the dashed box. M_1 and M_2 represent the actual transfer functions between the torque generated by the two movers and the mechanical speed, while $M_{1,em}$ and $M_{2,em}$ represent the transfer functions that the drive emulator should reproduce. It is worth to underline that in the active load case the drive emulator should add the emulated torque reference to the already present torque reference τ_2^* which drives the second mover.

Fig. 2. Block diagram of an active load emulation with an electrical drive.

In order to calculate the transfer functions between the torque contributions and the mechanical speed, the following

expression is obtained:

$$\begin{aligned}\omega_m &= M_1 \tau_1 + M_2 \tau_2 \\ &= M_1 C_1 \tau_1^* + M_2 C_2 (\tau_2^* + \tau_{em}^*) \\ &= M_1 C_1 \tau_1^* + M_2 C_2 \tau_2^* + M_2 C_2 R_{em} (\omega_{m,em} - \omega_m)\end{aligned} \quad (10)$$

By substituting the blocks inside the dashed lines, it follows:

$$\begin{aligned}\omega_m &= M_1 C_1 \tau_1^* + M_2 C_2 \tau_2^* + \\ &\quad + M_2 C_2 R_{em} (M_{1,em} C_1 \tau_1^* + M_{2,em} C_2 \tau_2^* - \omega_m)\end{aligned} \quad (11)$$

By grouping the terms with respect to the torque references τ_1^* and τ_2^* , it is obtained:

$$\begin{aligned}\omega_m &= (M_1 C_1 + M_2 C_2 R_{em} M_{1,em} C_1) \tau_1^* + \\ &\quad + (M_2 C_2 + M_2 C_2 R_{em} M_{2,em} C_2) \tau_2^* + \\ &\quad - M_2 C_2 R_{em} \omega_m\end{aligned} \quad (12)$$

from which the transfer functions can be directly obtained:

$$\begin{aligned}\omega_m &= \frac{M_1 C_1 + M_2 C_2 R_{em} M_{1,em} C_1}{1 + M_2 C_2 R_{em}} \tau_1^* + \\ &\quad \frac{M_2 C_2 (1 + R_{em} M_{2,em} C_2)}{1 + M_2 C_2 R_{em}} \tau_2^*\end{aligned} \quad (13)$$

By considering that $\tau_1 = C_1 \tau_1^*$ and $\tau_2 = C_2 \tau_2^*$, it follows:

$$\begin{aligned}\omega_m &= \frac{M_1 + M_2 C_2 R_{em} M_{1,em}}{1 + M_2 C_2 R_{em}} \tau_1 + \\ &\quad \frac{M_2 (1 + R_{em} M_{2,em} C_2)}{1 + M_2 C_2 R_{em}} \tau_2\end{aligned} \quad (14)$$

In a similar way to the passive load case, some conditions can be obtained in order to tune the regulator R_{em} . In this case, the following conditions occur:

$$\begin{aligned}\omega_m &\cong M_{1,em} \tau_1 + M_{2,em} \tau_2 \\ &\text{for } M_{1,em} M_2 C_2 R_{em} \gg M_1 \text{ and } M_2 C_2 R_{em} \gg 1 \\ &\text{and } M_{2,em} C_2 R_{em} \gg 1\end{aligned} \quad (15)$$

The conditions expressed in (15) are more stringent with respect to that in (9). The maximum torque that the drive emulator should produce can be calculated as follows:

$$\begin{aligned}\tau_{em,max}^* &= \max |R_{em} \Delta \omega_m| \\ &= \max |R_{em} [(M_{1,em} - M_1) \cdot C_1 \tau_1^* + \\ &\quad + (M_{2,em} - M_2) \cdot C_2 \tau_2^*]|\end{aligned} \quad (16)$$

This expression is slightly more complicate than that in (9), however it can still be easily used to determine the torque requirements for the emulator drive. By neglecting the contribution of C_1 and C_2 for the same reasons reported in Sect. II-A, the following final condition occurs:

$$\begin{aligned}\frac{\tau_{em,max}^*}{\tau_1^*} &\cong \max \left| R_{em} (M_{1,em} - M_1) + \right. \\ &\quad \left. + R_{em} (M_{2,em} - M_2) \frac{\tau_2^*}{\tau_1^*} \right|\end{aligned} \quad (17)$$

III. TUNING AND DIMENSIONING EXAMPLE

A tuning and dimensioning example has been performed on a mechanical system with two electrical motors connected through a non-rigid shaft. The diagram of the mechanical setup is reported in Fig. 3, with the parameters shown in Tab. I. J_1 and J_2 represent the moment of inertia of the two motors, B_1 and B_2 are the viscous frictions of the two motors, and K is the stiffness coefficient of the mechanical drive train.

Fig. 3. Mechanical test setup used for the simulations.

Tab. I
MECHANICAL SETUP ACTUAL PARAMETERS.

J_1	$Kg \cdot m^2$	8,0815e-004
J_2	$Kg \cdot m^2$	7,8315e-004
B_1	$N \cdot m/(rad/s)$	1e-3
B_2	$N \cdot m/(rad/s)$	1e-3
K	$N \cdot m/rad$	1450

The equations describing the dynamics of the system in Fig. 3 are the following:

$$\begin{aligned}\tau_1 &= J_1 \frac{d\omega_{m1}}{dt} + B_1 \omega_{m1} + K(\vartheta_{m1} - \vartheta_{m2}) \\ \tau_2 &= J_2 \frac{d\omega_{m2}}{dt} + B_2 \omega_{m2} + K(\vartheta_{m2} - \vartheta_{m1})\end{aligned}\quad (18)$$

from which it is possible to obtain the transfer function between τ_1 , τ_2 and ω_{m1} :

$$\begin{aligned}\omega_{m1} &= f_1(s)\tau_1 + f_2(s)\tau_2 \\ &= \frac{J_2 s^2 + B_2 s + K}{d(s)}\tau_1 + \frac{K}{d(s)}\tau_2 \\ d(s) &= J_1 J_2 s^3 + (J_1 B_2 + J_2 B_1)s^2 + \\ &\quad + (J_1 K + J_2 K + B_1 B_2)s + B_1 K + B_2 K\end{aligned}\quad (19)$$

The scope of the simulation is to move the resonant frequency of the system in Fig. 3 to a lower value. In this perspective, the parameters of the desired (to be emulated) mechanical system are reported in Tab. II. Note that the stiffness coefficient has been reduced by a factor of 1000.

The Bode diagram of the transfer functions $f_1(s)$ and $f_2(s)$ are reported in Fig. 4 and Fig. 5, respectively. Both the actual (dashed line) and the emulated (continuous line) transfer functions are drawn. The original resonant frequency is located around 304 Hz, while the desired (emulated) one is located around 9,6 Hz.

Tab. II
MECHANICAL SETUP DESIRED (EMULATED) PARAMETERS.

J_1	$Kg \cdot m^2$	8,0815e-004
J_2	$Kg \cdot m^2$	7,8315e-004
B_1	$N \cdot m/(rad/s)$	1e-3
B_2	$N \cdot m/(rad/s)$	1e-3
K	$N \cdot m/rad$	1,45

Fig. 4. Bode diagram of $f_1(s)$.

Fig. 5. Bode diagram of $f_2(s)$.

According to the analysis in Sect. II-B, a tuning of the regulator for the drive emulator was performed. C_1 and C_2 are approximated as a first-order transfer function with unitary gain and a bandwidth of 800 Hz, resembling the tracking capabilities of conventional current-controlled electrical drives. Following the condition in (15), the gain $M_2 C_2 R_{em}$ was evaluated, by tuning R_{em} as a series of a PI regulator (for good tracking performances) and a notch filter tuned to the actual resonant frequency of the system. The Bode diagram of the gain $M_2 C_2 R_{em}$ after the tuning of R_{em} is reported in Fig. 6. The dashed line has been drawn in order to highlight the cross-over frequency of the gain, which is taken as the bandwidth of the closed loop system. In this case, the cross-over frequency was set to 50 Hz, with a phase margin of 68 degrees.

The diagram of Fig. 6 does not immediately fulfil the conditions in (15). However, it is possible to plot the first transfer function of (14) and compare it with the desired model $M_{1,em}$. The result is shown in Fig. 7. The desired model is reproduced, including the new resonance, roughly until the bandwidth set by the regulator (50 Hz). It is not possible to

Fig. 6. Gain $M_2C_2R_{em}$ after tuning of R_{em} .

obtain any change in the mechanical system behaviour over the bandwidth, thus the original resonance is still present in the emulated model at higher frequencies.

Fig. 7. Transfer function $(M_1 + M_2C_2R_{em}M_{1,em}) / (1 + M_2C_2R_{em})$ against $M_{1,em}$.

Torque rating considerations have been also made by considering the expression (17), in the case of $\tau_1^* = \tau_2^*$ (which leads to two motors with the same torque range requested by the control, but not necessarily of the same torque/power rating). By substituting the corresponding transfer functions, the Bode diagram of the (17) has been drawn and reported in Fig. 8.

Fig. 8. $\tau_{em,max}^* / \tau_1^*$ for the simulated setup ($\tau_1^* = \tau_2^*$).

From Fig. 8 it is calculated that the drive emulator should be capable, in the worst case, of producing a torque reference $\tau_{em,max}^*$ which is almost 10 times (more precisely, 8,44 times)

higher than the maximum torque reference τ_1^* . This has a direct impact on the power rating selection of the second drive.

IV. EXPERIMENTAL RESULTS

Experimental results have been performed on a test-bench composed by two permanent-magnet machines in back-to-back configuration, each of them controlled by an ABB ACSM1 converter. A torquemeter was connected in between the two machines. The control board is composed by a Xilinx Virtex-6 FPGA evaluation board with two custom-made analog-to-digital (A/D) and digital-to-analog (D/A) converter boards. The two A/Ds are connected to the analog output of the ACSM1s (torque reference generated by the ACSM1s) while the D/As are connected to the analog input of the ACSM1 (torque reference signals for load emulation). Fig. 9a and 9b depict the test bench, while the machine parameters are reported in Tab. III.

Fig. 9. Test bench: (a) electrical machines, (b) FPGA and converters.

Tab. III
MOTOR PARAMETERS.

	Motor 1	Motor 2
Nominal power	1,48 kW	1,92 kW
Nominal speed	3000 rpm	3000 rpm
Nominal torque	4,7 N · m	6,1 N · m
Nominal current	3,7 A	4,3 A
Pole pairs	4	5
Inertia	$7,95 \cdot 10^{-4} \text{ kg} \cdot \text{m}^2$	$7,7 \cdot 10^{-4} \text{ kg} \cdot \text{m}^2$

The mechanical transfer functions $f_1(s)$ and $f_2(s)$ were identified first. With no active load emulation, the FPGA board generated a reference torque in the form of a chirp signal from 0,38 Hz to 300 Hz with steps of 0,38 Hz, changing frequency every 3 seconds. The signal was sent to one of two converters at the time, recording the torques (either τ_1 or τ_2) and speed (always ω_{m1}). A complete test was completed in around 52 minutes. The Bode diagram magnitudes of $f_1(s)$ and $f_2(s)$ are shown in Fig. 10 and 11.

The transfer functions fit well with the given inertia data obtained from the machine datasheets, including the torquemeter one. The presence of the resonance at around 200 Hz, instead of a slightly higher resonance as documented by the torquemeter datasheet (see Sect. III for the actual stiffness value), is not

Fig. 10. Original transfer function $f_1(s)$.

Fig. 11. Original transfer function $f_2(s)$.

surprising due to the presence of other mechanical connections on the same shaft.

The same tests were performed with the activation of the load emulation, according to the theory exposed in the Sect. II. The regulator for the emulation was tuned in order to give a bandwidth not bigger than 5 to 6 Hz. Fig. 12 and 13 show the Bode diagrams of the modified transfer functions, along with the emulated (desired) transfer function and the original transfer function. Results show a good agreement with the theory, and also show that the emulated transfer functions fall back into the original transfer function beyond the bandwidth of the regulator.

Fig. 12. Emulation of the transfer function from the original $f_1(s)$.

Fig. 13. Emulation of the transfer function from the original $f_2(s)$.

V. CONCLUSIONS

The paper discussed the emulation of mechanical systems by means of electrical drives, approaching the problem in a more general way. The basic cases of passive load and active load have been described, and conditions for the tuning of the regulator of the drive emulator have been obtained. Considerations regarding the bandwidth of the emulator and the rating of the machine/drive have been given. A tuning and dimensioning example has been performed on an active load case, where a resonant frequency has been moved to lower frequencies. Experimental results on a laboratory test bench, obtained through chirp signal injection and Bode diagram calculation, proved the effectiveness of the approach.

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