**Polytech'Orléans**

**p o l y t e c h n i q u e**

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# Master AESM

Motorization

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*Bruno Bonheur*

INTRODUCTION TO MOTORIZATION

**1-The engine from a functional approach:**

 The engine depends on a technical need expressed in a different discipline from that of electrical engineering. Electrical engineering can be considered as an application service.

This is one of the difficulties of this discipline, in which it is necessary to be familiar with the following user disciplines:

 - solid mechanics,

 - solar energies,

 - fluid mechanics,

 - traction vehicles

 These 4 fields, which are external to electrical engineering, constitute constraints on the discipline, as we shall see during this course.

 A considerable effort therefore needs to be made in defining specifications. This poses the more general problem of interdisciplinary communication.

 Many projects aborted in the past because of poorly defined specifications. That is why industry established standards for projects.

(example: the French standard Z 68-901 September 1992 revised in November 1996).

 Description of a SAP (automated production system) General cycle. Principles:

1 actions covering the study and decomposition of requirements on the descending branch.

2 - actions of verification on the bottom part.

3 actions to ensure consistency and verification. An action is definable if it is testable.

4 - The motorization part is only one V-cycle under the general V-cycle of the system.

Look at the V cycle from the top left to the top right (Appendix 1).

 **Needs Analysis:** it is expressed in terms of the user

 - move a load x(t), θ(t), v(t),(t).

 - ensure pressure on a hydraulic jack.

- ensure torque Tm(t).

**Functional specifications:**

This involves translating the specification into the technical language of electrical engineering.

There are three types of applications in motorization:

 - put in place : x(t), θ(t) law of position with or without enslavement

 - move : v(t) θ(t), rate with feedback control law

- Torque application → T(t) torque applied to wheels

##### Technical functions

They quantify functional information and collect information on safety standards or business type:

-safety of electrical operators - anti-explosion safety - electromagnetic compatibility

COMMENTS ON APPENDIX 2

 **(I1) static mechanical features**

The search for this point is carried out through knowledge of the point desired on the characteristic Text(Ω). It provides the numerical values of the nominal point, the number of energy quadrants solicited as well as the nominal power corresponding to the service type S1.

 **(I2) dynamic mechanical features**

Variation in speed or torque constraints is expressed by the laws Text(t) or Ω(t). These laws provide temporal constraints that then impose bandwidths. The question of the total or partial release of energy to the grid should also be dealt with.

 **(I3) type of command desired**

The needs analysis makes it possible to deduce the functions envisaged among the three mentioned. The nature of the controls by closed or open loop is then known.

 **(I4) economic and normative environment**

Environmental constraints such as maximum costs, available energy sources, and the electromagnetic environment modify the solution adopted. Among the economic criteria, it should be noted that in the economic criteria the power factor of the facility enables the grid to be sized at a lower cost.

 **(I5) technical skill and maintenance**

Using a technology involves training operators who can ensure maintenance and use. It is also a criterion of choice and an indication of the need for training.

**(I6) computerization of the site**

The level of computerization of the site must be consistent with the communication module of the machine. In a manufacturing process, machines must be computer-controlled or report their status to a supervisor.

Active portion of the descent (left-hand side of the V-cycle)

 Important : each stage must be testable.

##### Preliminary design

This step should propose a technical choice of power among the currently available resources, preferably optimized in terms of cost. The number of solutions must be defined.

##### Detailed design

This step defines all the components involved in the energy conversion chain.

- Engine pattern and reference

- converter class and reference

- the electro-mechanical control ensuring the safety of equipment and people

- mechanical mounting of all sensors external to the converter

- methods of communication

**The last step**

It comprises many technical activities such as:

- settings of the wiring devices

- in the case of equipment with an automation, writing the micro-code in a suitable language.

- the consistent installation of sensors

From the bottom to the top right of the V cycle

**Unit verification**

- reception of the individual elements, which should be tested if possible

- Tests concern only low requiments.

**Integration**

This step consists in ensuring:

* the consistency of devices, and the protection of the drives, engines, and sensors from the electrical, EMC, and geometrical points of view

**Verification of the technical specifications**

* carrying out specific tests.
* developing a series of tests that prove that the functions are accessible or exceeded (margins)

speed v (t) ((t)

maximum torque etc...)

**On service Test**

This step involves developing corresponding tests that are exactly defined using the specification level in automatic and/or manual steps defined for example by GEMMA.

An user’s guide must the records of these tests by the customer.

**Exploitation, optimisation, maintenance**

User’s role

**2 Let’s talk mechanics**

 **2.1 – Notations**

It is necessary to adopt clear notations for the frequent presence of energy reversibility in electrical engineering chains.

e .g. the well-known example of electric braking in railway traction.

We will limit our discussion to Rotary actuators.

They are known from the static point of view if their characteristic Tm(Ω) is known

 Ambiguity in the sign of the product TmΩ

 **Problem:**

What is the meaning of the sign of mechanical power Tm.Ω?

Receiver or generator ?

Let us return to thermodynamic conventions:

For an isolated system, when the energy is received, it is counted positive; When it is supplied by the system to the outside, it is negative, hence the following graphical notations:



## Therefore, in a power balance, **it will be counted positively.**

## **Simple Application** **; Electrical resistance**



2 energies: electrical and thermal

 Welec = Ri²t → dWelec = Ri²dt

 Wmeca = 0

 Wth = - KΔθt dWth = - KΔθdt

Δθ is given by the direction of the arrow

Δθ = θfinal - θinitial = θr - θa

 hence dWth = - K(θr - θa)dt

with K denoting positive thermal conductivity.

The graphic representation provides the following balance:

dWelec + dWth = 0 = Ri2 dt – K(θr - θa) dt

thus Ri² – K(θr - θa) = 0

 Ri² = K(θr - θa)

This equation states that the 2 amounts are positive, so if there is an RMS current (i²)

 θr is greater than θa.

 It is the joule heating effect.

**The engine rotating without loss**.



The receiver convention states that the received energy is positive.

dWs is the internal energy which consists in of magnetic energy in electrodynamic engines.

dWmeca describes the mechanical energy received

thus dWmeca= Text.dθ where Text is the sum of the external moments applied to the engine.

 For the torque of the engine Tm, the arrow of energy is placed in the other direction, denoted .dWmmeca=Tm.dθ

The mechanical energy provided by the engine becomes

 dWm meca = TmΩdt = - TextΩdt = - dWmeca

 Thus the energy balance can be written in 2 ways:

 dWelec + dWmeca = dWs dWelec = - dWmeca

 dWelec – dWm meca = dWs dwelec = + dWm meca

if the internal energy variation is null

hence the energy consequences are trivial.

 **If the machine uses electrical energy**  dWelec > 0

then dWmeca < 0 ⇔ TextΩ < 0

 dWm meca > 0 ⇔ TmΩ > 0

 **If** **the machine provides electrical power**  dWelec < 0

then dWmeca > 0 ⇔ TextΩ > 0

 dWm meca < 0 ⇔ TmΩ < 0

 steady state Tm = - Text or Tm + Text = 0

 **2.2 – Some typical mechanical characteristics**

**Drawing of Tm (Ω) in the 4 quadrants called the mechanical plane**



**Comments :**

**Constant resistant torque**

The characteristic of **lifting AB** is constant regardless of the speed.

 **A'B'** is discontinuous. It is placed in 2 engine quadrants. This is the case of **positive displacement pumping** which is possible in both directions from the point of view of the electric motor.

 Zero speed points correspond to the position of the load or torque retention function.**Variable resistant torques**

 **Friction**



**A** = adherence

**B** = dry friction –Text = - T0

**BC** = viscous friction 1st order –Text = - T0 - KΩ

 Tf = T0 + KΩ

**CD** = viscous friction 2nd order Tf = T0 +K1Ω + K2Ω²

Note the presence of strong nonlinearities and non-reversibility of the energy

**Electrical vehicle**:

It combines two modes:

- maximum torque at startup (low speed) mode

- speed development and command mode. It is friction + inertia



 **2.3** **Motor-load association**

 It is governed by the fundamental principle of Dynamics.



 Static study  : see section **2.1**

Let us plot the mechanical properties of a Tm (Ω) engine and any load Text (Ω).

The static study provides the operating points by the relationship:

Tm(Ω)+Text(Ω) = 0

Points A and B are points of static equilibrium

2 situations may be encountered:



From these points, it is shown by the term  = Tm+Text= Tm-(-Text)

Thus, left of the equilibrium point, Tm – (-Text) pointing downwards on Figure 1

 and upwards in figure

Then for ➀ ,  is negative so the speed decreases and the operating point of the engine slows down;

Then for ➁, is positive therefore the speed increases and tends to return to the equilibrium point B.

Thus :

 - A is an unstable equilibrium point.

 - B is a stable equilibrium point.

Two cases of a stable equilibrium point

 1 2



The two tubes, called of uncertainty tubes, take into account the possible dispersions of the engine characteristics due to the effect of: series, temperature, and aging.

As the speed belongs to the interval, it can slide into a domain

In case 2, this area is reduced.

The association between motor and load is more robust than that of case 1.

In case 2, when the load is the source of torque, the engine then behaves as the source of speed. This explains why case 2 is more robust.

Example: lifting ⇒ The speed must be command-driven.

Example: a run-of-river plant.

 Load : a water fall ⇒ pressure ⇒ source of torque.

 The associated asynchronous generator must be a source of speed to ensure a constant grid frequency.

 **2.4 – Notes on the ratio of the kinematic chain**

The weak point of engines is the fragility of their electrical insulation. These materials, produced by organic chemistry, cannot withstand temperatures above 300 ° C. It is therefore necessary to limit heating and hence the joule effect produced by the flow of current in the windings. Most machines have torque that is proportional to the effective intensity value or its square; limiting heating therefore leads to limiting the maximum engine torque available. Thus, the cost of a motor is linked to its nominal torque. In addition, speeds can reach 1500, 3000, 6000 rpm, a speed which is generally too high. We must reduce it with a gearbox.

 1st action : reduce engine torque with a mechanical gearbox



Note that: 

 T1 engine torque seen from the motor side.

 T2 engine torque when viewed from the load side.

First of all the efficiency of the gearbox is equal to unity.

  this explains the reduction effect.

 Ratio of the moment of inertia of the load to the engine shaft.

In PFD [Fundamental Principle of Dynamics] J1 is the moment of inertia of the motor seen from the motor side.

J2 is the moment of inertia seen from the load side. It is necessary to know the inertia of the motor side J’2. J’2 is obtained by using the conservation of kinetic energy of the load.

 thus, kinetic energy of the load: 

 Kinetic energy of the load seen from the engine side 

  

**Choice of the value of **

 A priori, the choice of  depends on a single analysis of velocities.

Ω2 is the functional specifications of the specification.

Ω1 is the standard values of common engines. Modern electrical engineering can adjust speed easily. This therefore opens up more possibilities and choices of . Law on the value of T1 when T2 is imposed then on the cost. A good choice of η makes it possible to optimize the engine and the associated drive in terms of cost.

Several cases of load can be taken into account.

 a) loads dominated by viscous friction of the 1st order.

 b) loads dominated by inertias.

 c) mixed loads.

 Engine friction load friction seen on the motor side



**In Case a it becomes**

 

The engine is optimized if the torque is minimal for the desired speed thus

 must be minimal

  

 This is minimal because the derivative is negative when η is low.

**In Case b it becomes**

 

 This ratio should be as low as possible it is acquired for : 

**In Case c it becomes**

 

 

 Hence the optimization provides 

**APPENDIX 1**



### APPENDIX 2

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | inputs | BLOCS |  | outputs |
|  |  |  |  |  |
| E1 | Text(Ω) résistantde l’application et les points ou la zone de foctionnement désiréesollicitation s dans le temps  | I1fonctionnalitésmécaniquesstatiques | →→ |  R1 Determination du service type S1 ou autre R2 Dans le cas service S1 valeurs numériques nominales de la vitesse et du couple |
|  |  | ↓ |  |  |
| E2 | Cycle typiqued’utilisation Ω(t) et Tm(t) | I2fonctionnalités | → | R3 signes nombre de quadrants du plan mécanique utiles en régime permanentR4 bande passante ou temps de réponse des dispositifs |
|  |  | mécaniques |  |  |
| E3 | Définition des temps de cycle et des performances de temps de réponse attendus | dynamiques | → | R5 réversibilité électrique vers le réseau d’alimentation |
|  |  | ↓ |  |  |
| E4 | fonctions envisagéesmise en positionserragemise en vitesse | I3type de commande souhaitée | → | S6 nature des contrôles avec ou sans bouche fermée position, vitesse, couple. |
|  |  | ↓ |  |  |
| E5 | maximums sur lescoûts | I4Environnements |  |  |
| E6 | CEM sécurité et des personnes et des installations | économique | → | R7 boucles ouvertes ou fermées |
| E7 | restriction sur lessources d’énergiedisponibles | ettechnique | → | R8 choix de la technologie hydraulique, pneumatique, électrique |
|  |  | ↓ |  |  |
| E8 | encombrements etpuissance massiquenominale | I5Compétence requise et maintenance | →→ | R9 installation puissanceapparente à installer enfonction de la puissance utileR10 maintenance suivanttechnologie envisagée |
|  |  |  |  |  |
| E9 | Communication ------ | I6 informatisation du siteNiveau CIM |  | S11 compatibilité des réseaux industriels ------ |

**Electromagnetic energy conversion:**

**1/Converting electromagnetic energy:**

  **Energy balance**:

We are interested only in electro-mechanical systems with one degree of freedom such as bonds slides following an x axis and angle parameter pivot θ.

 **thermodynamic convention**: energy is counted positive

mechanical interaction dWmeca=Text.dθ ou Fext.dx

thermal interaction dWth = -K.ΔT.dt

electrical interaction for a dipole dWelec= ui.dt

 variation in internal energy stored in magnetic form dWs

Remark :

We do not consider here the possibility of storing mechanical energy in kinetic form, so all balances are carried out at engine stop. For the sake of simplicity, mechanical dissipation is neglected. Thus the forces and torque that appear are the potential exchanges with mechanical systems. For example the bearings of the shaft are already considered as components that are external to electromechanical processes.



**Figure 1**

Thus dWth +dWmeca +dWe= dWs

Let us develop the electrical energy term: for a dipole its value is: dWe=ui.dt

The law of the coil in receiver convention is written: u= ri – e

With e denoting a Lenz generator defined by Faraday’s law: 

Thus dWe= ri2dt + idt

Inserting this equation in the energy balance gives:

dWs= dWth +dWmeca+ ri2dt + idt = -KΔTdt + ri2dt + dWmeca + i.dt

The joule effect is the direct conversion of electrical energy into thermal energy; there is a loss of 2 terms. See Section 1.2 in the Introduction to motorization.

Thus dWs = dWmeca + i.dφ

It is generalizable to structures l windings and j. degrees of freedom in the form:



This equation indicates that there may be 2 causes of the increase in the energy stored in magnetic form:

-variation of mechanical energy

-energy modification of the electrical source.

-or both at once.

ThusΔWs is a function two variables φ and x (θ) : ΔWs(φ,x ( θ))

This can be written in the form:



For rotative systems

 **1.2** **Evaluation of stored energy and coenergy**:

Here, we study the case where the mobile part is stationary or nearly fixed to introduce a new magnitude, called co-energy. It will be seen that this provides a more realistic picture.

Under this hypothesis : dWmeca = 0 ⇒ dWs = idφ

The increase in stored magnetic energy is linked to a variation in the flow. The relationship Φ(i) is known for a particular machine geometry. This Law inherits the saturable shape of the ferromagnetic materials that constitute the magnetic circuit. The presence of an air gap means that hysteresis can be neglected.



The hatched surface corresponds to the elemental energy idφ

Thus the increase in energy from 0 to F is obtained:



The surface OCFE represents this energy. Co-energy is defined by the complementary part OCFG.

 in point **F**



Thus 

This relationship allows us to express the co-energy from the movement and the current without postulating that the device is fixed.



It denotes the fact that co-energy is a function which depends on the intensity and the size of mechanical displacement.

Thus : 

This new expression has the advantage over the energy differential of depending on 2 easily measurable quantities such as the position and the current. It must be admitted that the measurement of flow is not easy and can be costly.

 **1.3 Expression of the moment or obtained force:**

The external moment or force are obtained by identifying the 2 expressions obtained for co-energy.

Thus:

The presence of the minus sign is less consistent with the definition of the external magnitude that is the opposite of the action of the engine (Tm, Fm) on the outside.

 **Case of linear systems**:

A linear system is characterized by the absence of saturation. The characteristic of the material φ(i) for a position of the mobile part is a straight line passing through the origin.

 Thus the notion of inductance has a real meaning:



In reality, as shown above, magnetic materials are not linear but can be partially linearized if the presence of an air-gap enables hysteresis to be neglected.

Where the application to a rotation or a translation:





In the case of systems in several circuits, current i becomes the vector current [I] and the inductance l becomes matrix [L (x or ())]. These formulae are used to calculate the force or torque exerted at every moment (at each step of calculation) if the matrices [L (x)] or [l(θ)] are known by the rules of construction for the machine. Knowing that Text is the opposite of the engine torque, we can then estimate the torque at every moment without measuring. It is an estimator of torque.

Exercise: Construct the matrix of a machine with 2 inductance windings.

Flow equation:

 or 

and 

Calculation of the co-energy by half of the surface 

Hence the general expression of engine torque:



**2 Case of the second kind of machine:**

Explanation for the study of this machine.

 It will be seen later with the Kapp and Concordia transformation that a three-phase induction machine studied in mechanical terms can be strictly defined by 2 dimensions. Thus the stator and rotor windings can be represented by 2 coils set π/2

Electrical convention motor

Magnetic field law B(θ)= 

Θ is the angle which locates the rotor in the stator coordinates.

The rotor has non-salient poles, thus its reactance is invariant by the rotation of the rotor.

Hence in the following figure:



Figure 2

For each i in the stator winding, we can write the flow equation:

 for example, the 1 of the stator coil.



In fact there are four flows which are the components of the flux vector, denoted [φ]



where [L] is the 16-component inductance matrix



After hypothesis :

 its reactance is constant.

 In addition there are the relations: LS1 = LS2 = LS  et LR1 = LR2 = LR

 The couplings between the same armature windings are almost zero because the coils are placed in quadrature π/2.

thus: MR1R2 = MR2R1 = MS1S2 = MS2S1 = 0

Mutual inductance coefficients are equal to their reciprocal:

MSR = MRS

The mutual inductance between the stator and rotor windings has sinusoidal variations. This is a consequence of the assumption of sinusoidal distribution fields.



# FIGURE 3

Hence the expressions of mutual inductance.

MS1R1 = MR1S1 = MR2S2 = MS2R2 = Mm cosθ

MS1R2 = MR2S1 = Mm cos(θ+π/2) = -Mmsin(θ)

MS2R1 = MR1S2 = Mm cos(θ -π/2) = Mmsin(θ)



The calculation of electromagnetic torque uses the derivative (this inductance and matrix):

  avec 

This gives : 

It can be seen that the torque is provided by the interaction of currents.

Let us consider two-phase power supplies with the following notations:

calculate the following quantities:





Thus the torque : 

The time phase is expressed as:



 As a result of the presence of inertia, the mechanical part is sensitive to the average torque value. This value cannot be non-zero if the dependency t is cancelled. This is done for the following equality:

**ωS-ωR-pΩ=0**

This equation leads to the following overall picture:

|  |  |  |  |
| --- | --- | --- | --- |
| ωs | ωr | pΩ | comment |
| 0 | ≠0 | ≠0 | ωr =-p Ω DCM |
| ≠0 | 0 | ≠0 | ωS = pΩ SM |
| ≠0 | ≠0 | ≠0 | ωR = ωS-pΩ IM |

The first line deals with continuous motors.

 The second deals with synchronous motors.

The third deals with asynchronous motors.

So we can consider the same system to explain the principal laws for electrical rotative engines.

The DC machine is the oldest engine, which has now been discarded because of the heavy maintenance required and a higher cost. It is however important in helping to understand the others because the equations are simpler.

The Synchronous machine, known as brushless motor, is the most efficient motor and has replaced the DC machine in all of its applications, particularly in the automotive field.

The Induction Motor is the most popular electrical motor for industrial needs.