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Comparative Study of a Thermal and Electric Motor

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Abstract: The transportation sector has undergone many profound changes, a true revolution occurred in the 20th century with the widespread adoption of the internal combustion engine which uses fossil fuels, relatively available and simple to use.

Despite the decrease in emissions in the Organization for economic cooperation and development OECD countries, the countries emitting the most greenhouse gases linked to transportation, the sector's contribution to global GHG emissions increased by 18% over the 2000-2010 periods. This industrial environment has changed greatly because we are no longer in an era where demand exceeded supply. Currently, supply is significantly higher than demand, and companies are seeking to improve and better manage their production while reducing costs.

In return, the electric motor in the vehicle today implies a significant additional cost that will have to be recouped by the driver through reduced consumption and, in the longer term, through the benefit of additional features. This additional cost will be all the more significant as the degree of vehicle electrification and the features provided by this motor are substantial.

Keywords: Include a list of 5-10 keywords.

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1. INTRODUCTION

The industry is currently at the heart of a major technological revolution, driven by environmental issues and the need to reduce greenhouse gas emissions. While traditional internal combustion engines still dominate the market, new propulsion technologies are emerging, offering more environmentally friendly alternatives. Among these are electric motors.

Electric motors, powered by rechargeable batteries, allow for zero-emission and silent driving. Although limited by their range, constant progress is being made to increase the energy density of batteries and optimize energy management. Electric motors offer an interesting compromise in terms of electrical power and speed performance as well as a decrease in total losses.

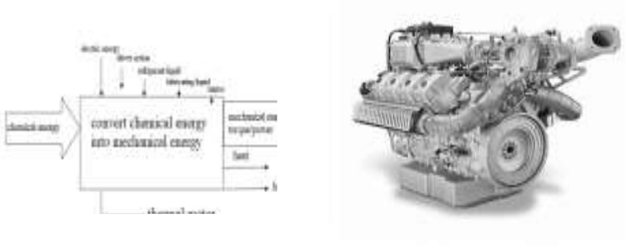
2. OPERATION MODE OF THE MOTORS

The engine is an essential device that converts various forms of energy into mechanical energy, thereby enabling the operation of different types of machines and vehicles. Engines can be classified into several categories based on their energy source, such as thermal, electric, and hybrid engines. The operating mode of an engine involves several key steps, including the intake of fuel or energy, the conversion of this energy into heat or motion, and finally, the production of useful mechanical energy to perform work. Understanding how engines operate is fundamental for improving their efficiency, reducing pollutant emissions, and innovating in propulsion technologies.

2.1 Operation of an Internal Combustion Motor

The internal combustion motor receives gasoline, the fuel from the carburetion system. It generates energy through compression. This combustion is triggered by the ignition system. It produces mechanical energy available at the flywheel. It releases burnt gases. It evacuates heat through its cooling system. It receives the high-voltage electric current necessary for ignition. The driver engages the starter. The engine receives the mechanical energy necessary for its start-up from the starter. It also receives the lubricant necessary for the operation of its lubrication system. It converts the chemical energy in the fuel into heat energy, and then it converts this heat into mechanical energy (work)[1].

Figure 1 thermal motor mode



2.2 Operation of an Electric Motor

The electrical system of the motor consists of:

- An electrical reserve made up of one or more batteries;
- A charging circuit, including an alternator and a regulator that ensures, during engine operation, the recharging of the battery and the power supply to various accessories.
- A starting system allowing the propulsion unit to be started. Current legislation requires that the battery be able to perform at least six consecutive starts without recharging.

Initially, the battery begins to supply energy to the stator, which generates the magnetic field that rotates the rotor. This mechanical energy reaches the wheels through the transmission, and the vehicle is propelled as long as the accelerator is pressed. When the pedal is released, the magnetic field is interrupted, and the rotor turns freely while acting as an alternator that recharges the battery[2].

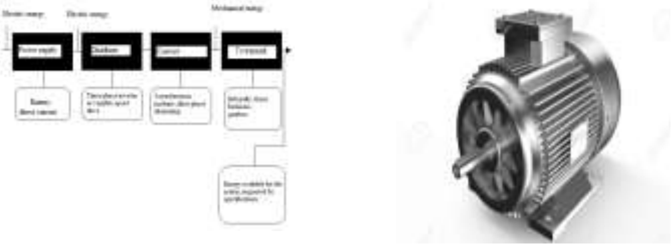


Figure 2 .electric motor mode

3. MODELING AND SIZING

The study of any physical system requires modeling. This allows us to simulate the system's behavior in response to different stimuli and thus understand the mechanisms governing its operation. Modern control laws, which are increasingly efficient, allow for better control of transient regimes while ensuring precise speed regulation over a wide operating range. All these improvements require a good understanding of the machine and its converter, especially in transient regimes. In our case, we will deduce design laws adapted to thermal and electric motors:

3.1 Thermal motor:

The thermal engine is a very complicated system, but it is simply considered as a torque generator, which is a source of propulsion. In this work, a 57 kW engine was chosen [2]. The SIMULINK block used for the simulation is shown in figure (3):

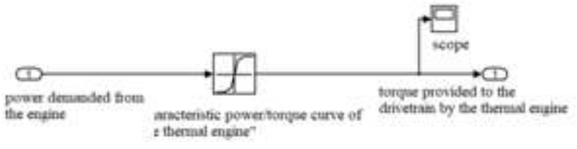


Figure 3 SIMULINK block of the thermal engine

The gearbox functions to multiply the engine torque by the speed reduction, which is necessary to keep the engine at a constant rotational speed as much as possible to maintain a satisfactory torque. To maintain constant power to the transmission, if the wheel speed ω_r decreases, the torque T_r applied to the wheel axle must increase in the same proportion. Knowing that[3]:

$$T_a \ \omega_a = T_r \ \omega_r = cst \tag{1}$$

Where:

T_a : Torque provided by the engine to the primary shaft.

ω_a: Rotational speed of the primary shaft.

T_r: Output torque from the gearbox applied to the wheel axle.

ω_r: Rotational speed of the wheel axle.

We deduce that:

$$T_r = T_a \frac{\omega_a}{\omega_r} \tag{2}$$

The ratio $(\frac{\omega_a}{\omega_r})$ is the ratio to be applied to the engine torque T_a to multiply its value, and it allows the calculation of the torque T_r applied to the wheel axle. It is generally called the torque ratio (r).

Figure 4. Epicyclic gear train

The dynamic model of the epicyclic gear train is given by the following expression:

$$T_s = (\frac{k_b}{k_b - 1})T_{MT} \tag{3}$$

And

$$T_{GE} = (\frac{-k_b}{k_b - 1})T_{MT} \tag{4}$$

Where:

T_s: Torque provided by the output shaft to the drivetrain.

T_{MT}: Torque exerted by the thermal engine on the epicyclic gear train.

T_{GE}: Torque provided by the epicyclic gear train to the electric generator.

The relationship between the different rotational speeds is given by the following kinematic law:

$$\omega_{GE} + (k_b - 1) \ \omega_{MT} - k_b \ \omega_s = 0 \tag{5}$$

Where:

ω_s: Rotational speed of the output shaft, which is equal to the rotational speed of the electric motor.

ω_{GE}: Rotational speed of the generator.

ω_{MT}: Rotational speed of the thermal engine.

k_b: Transmission ratio.

For the simulation, we have taken Kb = -2.6.
The SIMULINK block used for the simulation is as follows

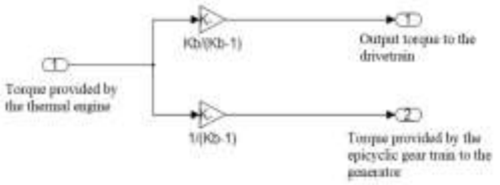


Figure 5. SIMULINK block Epicyclic gear train

3.2 Electric motor:

In this section, we present the model of the permanent magnet synchronous machine
The Permanent Magnet Synchronous Motor (PMSM) is widely used in various industrial and domestic applications due to its high efficiency, superior power density, and excellent torque-to-weight ratio. Unlike conventional DC motors that use brushes and a commutator for commutation, permanent magnet motors use permanent magnets attached to the rotor, eliminating the need for brushes and reducing maintenance and losses [4].
A synchronous motor with magnets has a stator winding with three phases named a, b, and c and permanent magnets on the rotor (figure 6).

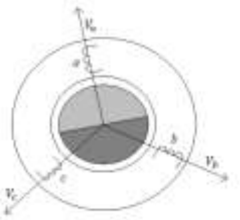


Figure 6. Representation of the windings of a synchronous motor with magnets in the electrical plane

The stator winding, driven by a balanced three-phase system of currents with pulsation ω_s, creates a rotating magnetic field in the air gap at synchronous speed Ω_s, with p pairs of poles:

$$\Omega_s = \frac{\omega_s}{p} \tag{6}$$

The magnetic field generated by the magnets is fixed relative to the rotor. The interaction between the stator's rotating field and the rotor's fixed field creates a torque whose average value is zero. The modeling is based on a number of assumptions [4]:

- The motor has perfect three-phase symmetry in construction.
- The effect of slots is neglected.
- The spatial distribution of the magnetic field in the air gap is sinusoidal.
- The magnetic circuit is linear; saturation, hysteresis, and ferromagnetic losses are not considered.

$$\begin{cases} V_a = Ri_a + \frac{d\Psi_a}{dt} \\ V_b = Ri_b + \frac{d\Psi_b}{dt} \\ V_c = Ri_c + \frac{d\Psi_c}{dt} \end{cases} \tag{7}$$

These relations can be written in the following vector form:

$$\boldsymbol{V} = R\boldsymbol{I} + \frac{\mathrm{d}\Psi}{\mathrm{dt}} \tag{8}$$

The moment of the electromagnetic torque can be calculated by the general formula related to the electromagnetic converter with magnets:

$$\gamma = I' \frac{\Psi_0}{d\theta} + \frac{1}{2} I' \frac{dL}{d\theta} I \tag{9}$$

Since the inductance matrix only includes constants, the formula is reduced to:

$$\gamma = I' \frac{\Psi_0}{d\theta} \tag{10}$$

The calculation can be developed:

$$\gamma = [i_a i_b i_c] \begin{bmatrix} -\rho\Psi_0 \sin \rho\theta \\ -\rho\Psi_0 \sin\left(\rho\theta - \frac{2\pi}{3}\right) \\ -\rho\Psi_0 \sin\left(\rho\theta + \frac{2\pi}{3}\right) \end{bmatrix} \tag{11}$$

Let's perform the matrix product:

$$\gamma = -\rho\Psi_0 \left[i_a \sin \rho\theta + i_b \sin\left(\rho\theta - \frac{2\pi}{3}\right) + i_c \sin\left(\rho\theta + \frac{2\pi}{3}\right) \right]$$
(12)

We modify this expression using the trigonometric formula:

$$\sin\,(\mathrm{a} + \mathrm{b}) = \sin \mathrm{a}\ \cos \mathrm{b} + \ \sin \mathrm{b}\ \cos\ \mathrm{a}$$

This leads to:

$$\gamma = \rho\Psi_0 \left[\left(-i_a + \frac{1}{2} i_b + \frac{1}{2} i_c \right) \sin \rho\theta + \right.$$
$$32 ib - ic \cos\rho\theta \tag{13}$$

For the electromagnetic torque and the motor's mechanical equation, the expression is given by:

$$J \frac{d\Omega_r}{dt} = \gamma - T_r - f\Omega_r \tag{14}$$

With:

$\Omega_r = \omega/p$: Rotation speed of the machine
p: Number of pole pairs
γ: Electromagnetic torque
T_r: Load torque
J: Total moment of inertia referred to the rotor shaft

The electric engine used in applications requiring autonomous power, like electric vehicles, they are paired with batteries. This battery is the component that ensures the storage of electrical energy, and knowing its charge level is essential to activate or deactivate the electric motor.
For our study, a precise model of a battery is necessary.

We will provide a model of a battery that is widely used in electric cars (Ni-MH Battery, 200V, 6.5Ah),

The mathematical model of the battery is given by the following expression [5]:

$$E = E_0 - K\frac{Q}{Q - i_t} + A\,exp(-Bit)$$

And the mathematical expression for the state of charge of the battery is given by:

$$EDC = 100.\left(1 - \frac{1.05Q}{\int idt}\right)\%$$

Where:

- E: Open-circuit voltage.
- E_0: Full charge voltage.
- K: Polarization index.
- Q: Battery capacity.
- A: Exponential voltage.
- B: Exponential capacity.
- I: Current intensity

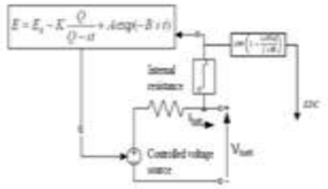


Figure 7.Schematic representation of the battery model in SIMULINK.

In summary, PMSM represents a key technology for many modern applications due to their efficiency and performance. However, their integration requires complementary components like batteries and sophisticated management systems to fully exploit their potential.

4 RESULTS AND INTERPRETATION

The input signal is the desired power calculated by the onboard supervisor. This power is compared with the characteristic torque/power curve of the thermal engine. After comparison, the output is the torque to be provided to the system via the thermal engine. The characteristic torque/power curve is given in the figure 8

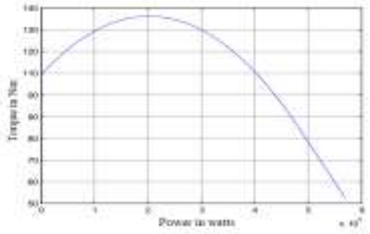


Figure 8. Characteristic curve (torque/power) of the thermal engine used for simulation

To calculate the torque requested, we compared the rotational speed of the transmission shaft with the characteristic torque/speed curve of the electric motor (Figure 9) to find the maximum torque that the electric machine can provide at this rotational speed. Then, we multiplied this maximum torque by the accelerator position, which is given in percentage (%). For the calculation of the power requested by the driver, we simply multiplied the rotational speed of the transmission shaft by the desired (requested) torque.[5]

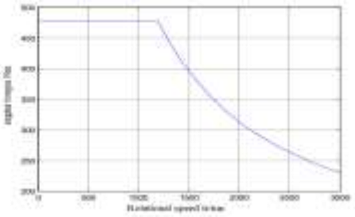


Figure 9.Characteristic torque/speed curve of the electric motor

Generally concerning the results obtained, electric motors offer superior energy efficiency, reduced environmental impact, and lower maintenance costs compared to thermal engines. However, thermal engines benefit from a more developed refueling infrastructure and currently offer greater range. As battery technology and charging infrastructures advance, it is likely that electric motors will become increasingly dominant, especially due to their long-term environmental and economic advantages.

6. CONCLUSIONS

Each engine has its own advantages and disadvantages. Therefore, combining thermal and electric motors in the same machine allows for maximizing the benefits of each type of engine while minimizing their drawbacks. Hybrid systems offer superior energy efficiency, reduce greenhouse gas emissions, increase range, and improve driving comfort. This synergy makes hybrid vehicles an attractive option for consumers looking to combine performance, economy, and environmental responsibility

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