

Development of High-Power and High-Efficiency Motor for a Newly Developed Electric Vehicle

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ABSTRACT

This paper describes the development of the drive motor used on a newly developed electric vehicle (EV) that has been specifically designed and engineered as the world's first mass-produced EV. Producing maximum torque of 280 Nm and maximum power of 80 kW, this synchronous motor was selected as the first electrified powertrain to be named to Ward's 10 Best Engines list for 2011. In developing this motor, magnetic field simulations were conducted in the process of adopting the following in-house technologies to achieve a compact motor size, high output and high efficiency.

The rotor shape has the interior permanent magnets arranged in a ∇ -shaped that achieves a superior balance of torque and power. The flux barriers located on the outer periphery are designed to reduce iron loss. The V-shaped flux barriers provide both excellent mechanical strength and outstanding performance during high-speed motor operation. The motor is built with segmented magnets that reduce eddy current losses to improve continuous output performance.

The results of magnetic field simulations and mechanical strength simulations are presented along with a description of each of the unique technologies adopted.

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INTRODUCTION

For the automotive industry, the development of zero-emission vehicles that have virtually no environmental impact during operation represents the optimum long-term approach to protecting the environment and generating product demand. At Nissan, we have positioned the introduction and popularization of zero-emission electric vehicles (EVs) at the core of our corporate strategy and are committed to being a global leader in zero-emission vehicles.

The company has released and marketed numerous EV models since putting its first EV on the market in 1947. A mass-produced EV model for global markets and featuring dedicated styling and design has been successively released in the United States, Japan and Europe since late 2010.[1] The 80-kW AC synchronous electric motor powering the new Nissan LEAF EV became the first drive motor in history to be named to Ward's 10 Best Engines list for 2011.

This paper describes the innovative technologies incorporated in this electric motor.

MOTOR OVERVIEW

The motor and inverter have been developed specifically for a newly developed EV, which involved optimizing the relationship between current and torque/power output. [Figure 1](#) shows the relationship between the characteristics of the electric powertrain and the required vehicle performance in terms of driving force and vehicle speed. With the electric powertrain supplying maximum torque of 280 Nm and maximum power of 80 kW, the newly developed EV provides ample practical performance comparable to that of gasoline-engine vehicles, including a top speed of 145 km/h and gradability of 30%.

The efficiency of the electric powertrain is shown in [Figure 2](#). In this figure, the electric powertrain comprises the motor, inverter and AC cables connecting them. The system achieves high efficiency of nearly 95% at the most efficient operating point. At the weighted average of the operating points used most frequently by the vehicle, this electric powertrain still delivers high efficiency of over 90%.

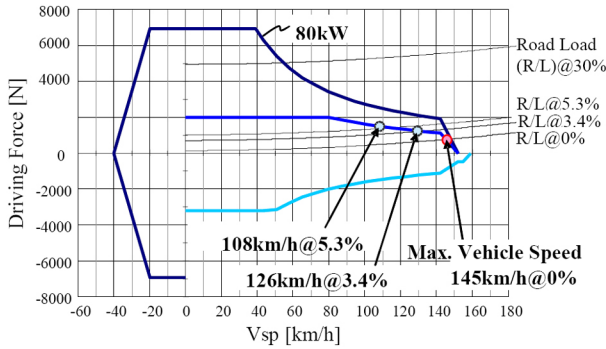


Figure 1. Dynamic performance

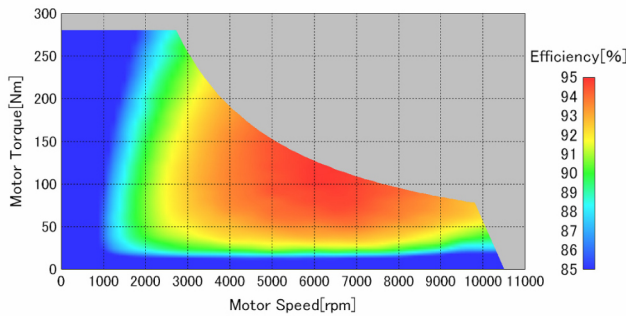


Figure 2. Efficiency of the electric powertrain



Figure 3. Appearance of motor

Table 1. Comparison of motor specifications

Performance	Newly developed	Hypermini
Max. torque	280 Nm	130 Nm
Max. power	80 kW	24 kW
Top motor speed	10,390 rpm	6,700 rpm
Motor mass	Approx. 58 kg	Approx. 54 kg
Cooling	Water	Water

MAGNETIC CIRCUIT DESIGN

A permanent magnet synchronous motor generates torque in accordance with the expression in Eq. (1), where P is the number of poles, ϕ_a is the interlinkage magnetic flux, L_d and L_q are the inductance of the dq axes, and i_d and i_q represent the current of the dq axes.

$$T = \frac{P}{2} \{ \phi_a i_q + (L_d - L_q) i_d i_q \} \quad (1)$$

Here, the first and second terms of Eq. (1) express the permanent magnet torque and reluctance torque, respectively.

Because an interior permanent magnet (IPM) motor generally has inverse saliency, $L_d < L_q$ and $(L_d - L_q)$ is negative, making it possible to obtain positive reluctance torque by controlling i_d using a negative value. It is clear that ways of increasing torque under a given current level including making ϕ_a larger or increasing the inductance difference $(L_d - L_q)$, i.e., increasing L_q and reducing L_d .

On the other hand, let us consider the motor output in the region of field-weakening control that controls the back EMF of the motor at high speeds so that it does not exceed the battery voltage. As shown in Fig. 5, the maximum motor output increases as the ratio of the interlinkage magnetic flux ϕ_a to the d-axis inductance L_d (ϕ_a/L_d) becomes larger.

However, as (ϕ_a / L_d) increases, the field-weakening current needed to control the motor output to a zero state also increases. Consequently, efficiency declines in the low output region and also more current is needed to produce the desired output, thus requiring a larger drive inverter. Therefore, in designing the magnetic circuit of a motor, it is essential to design motor constants (ϕ_a , L_d and L_q) that match the desired torque and power levels.

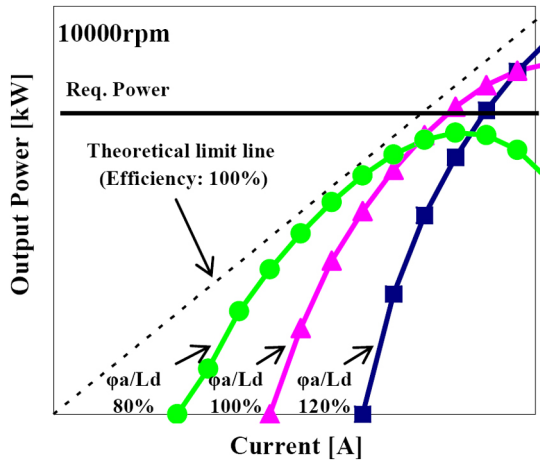


Figure 5. Motor output for various parameters

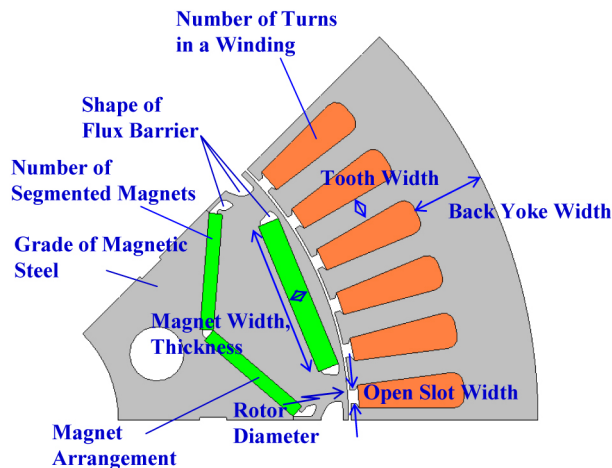


Figure 6. Parameters for magnetic circuit design

In order to achieve these motor constants, it is necessary to optimize many motor parameters as shown in Fig. 6. The electromagnetic steel sheet used in motors is characterized by magnetic saturation and nonlinear properties. Moreover, the rotor also has a complex shape. For these reasons, magnetic field simulations and strength simulations were used to examine the shape of each part. Figure 7 shows a typical example of the results of a magnetic field simulation.

The following sections describe the results obtained in this study concerning the magnet arrangement, flux barrier geometry and magnet segmentation, which are three especially important shape elements of the rotor of an EV motor. These results were incorporated in the motor used on the new EV.

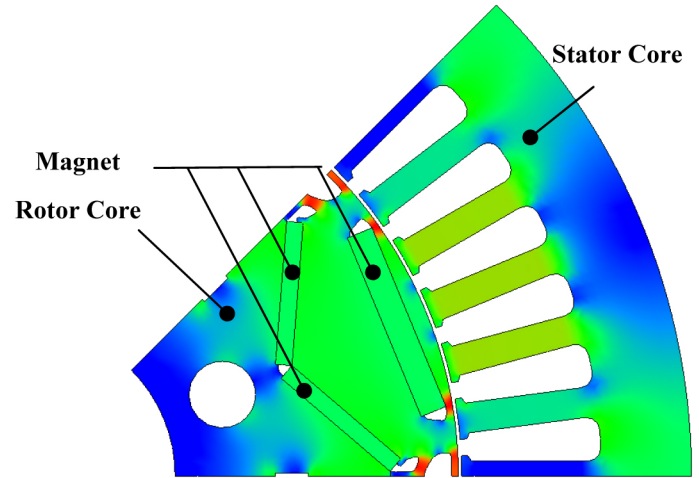


Figure 7. Magnetic field simulation results

MAGNET ARRANGEMENT

An IPM motor allows more degrees of design freedom than a surface permanent magnet (SPM) motor because the magnets can be embedded. The type of magnet arrangement that is selected is particularly important because it has a profound impact on motor characteristics. [2]

In developing the motor for the new EV, a comparative study was made of an I-shaped, a V-shaped and a ∇ -shaped magnet arrangement in order to select the best type for the motor. Figures 8,9,10 show the rotor shapes that were examined in this study.

A constant quantity of magnets was used in each case in order to compare accurately the motor characteristics attributable to the differences in the magnet arrangement. A centrifugal force analysis was conducted to determine the bridge shape at the ends of the magnets so that the stresses generated in the electromagnetic steel sheet would be equal. In addition, the layer thickness, stator geometry, number of turns, and current were the same in each case and the motor output characteristics were calculated in magnetic field simulations.

Figure 11 compares the maximum torque obtained with each magnet arrangement and Figure 12 compares their maximum power in the high-speed region.