新型日産リーフの電動パワートレイン

Electric Powertrain for the New Nissan LEAF

NISSAN MOTOR CORPORATION
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## 目次

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◆ 巻頭言

自動車大転換期を迎えて－環となる新型日産リーフのEV技術 ............................... 鳥海 真樹 ........................ 1

---

◆ 特集：新型日産リーフの電動パワートレイン

1. 日産電気自動車用パワートレインの進化 ................................................................. 小野 山田一・吉本 貫太郎 .................. 3

2. 新型日産リーフ用高性能モータ＆インバータシステム ................................. 並木 一茂・百瀬 友昭

   正治 滝博・室田 浩平 .................. 8

3. 新型日産リーフの電動パワートレイン制御システム ................................. 關 義治・黒澤 崇央

   吉本 貫太郎・島村 青之 .................. 16

4. モータ制御によるバックラッシュ振動の抑制 ................................ ....... 大野 翔・澤田 彰・小松 弘証

   藤原 健吾・中島 孝 .................. 23

5. 新型日産リーフのe-Pedalシステム ................................................................. 宮下 直樹・新藤 郁真・鈴木 進也

   島代 圭悟・中村 洋平 .................. 30

6. 新型日産リーフ向け大容量リチウムイオンバッテリ ................................ 田崎 信一・髙松 俊文・蕨山 康介

   坂本 涼・岩下 健児・東野 龍也・小比賀基治 .................. 40

7. 急速充電の現状と今後の発展 ................................................................. 吉崎 和也・上島 宇貴 .................. 48
◆ 技術紹介

8. 世界初可変圧縮比エンジン 新型KR20DDET "VCターボ"の開発

松岡 一哉・木賀 新一・小島 周二・茂木 克也・高橋 英二 …… 53

◆ 新車紹介

9. 新型日産リーフ商品概要…………………………………………………………………………………福田 真人 …… 62

10. 新型INFINITI QX50商品概要 …………………………………………………………………………角 智彰 …… 67

◆ 社外技術賞受賞一覧表 ………………………………………………………………………………………… 72

◆ 受賞技術概要

11. 可変磁力モータの高速領域における磁性時電圧上昇の抑制及び、磁性制御に伴うトルク脈動に関する考察

佐々木健介・カガス プレント・福重 孝志・加藤 崇・赤津 創・ローレンツ ロバート …… 76
◆ Preface

EV Technologies of the New Nissan LEAF
—Providing the Foundations Ushering in a Major Turning Point for Vehicles

By Masaki Toriumi

◆ Special Feature: Electric Powertrain for the New Nissan LEAF

1. Evolution of Electric Powertrain for Nissan Electric Vehicle

By Taiichi Onoyama, Kantaro Yoshimoto

2. High Performance Motor and Inverter System for the New Nissan LEAF

By Kazushige Namiki, Tomoaki Momose, Mitsuhiro Shouji, Kohei Murata

3. Electric Powertrain Control System for the New Nissan LEAF

By Yoshinori Seki, Takahisa Kurosawa, Kantaro Yoshimoto, Seishi Shimamura

4. Drive Motor Control Method for Suppressing Drive Shaft Torsional Vibration due to Gear Backlash

By Sho Ohno, Akira Sawada, Hiroyuki Komatsu,
Kengo Fujiiwa, Takashi Nakajima

5. e-Pedal System of the New Nissan LEAF

By Naoki Miyashita, Ikuma Shindo, Tatsuya Suzuki,
Keigo Ajiro, Yohei Nakamura

6. High-capacity Lithium-ion Battery for the New Nissan LEAF

By Shinichi Tasaki, Toshifumi Takamatsu, Kousoke Hagiya, Ryo Sakamoto,
Kenji Iwashita, Tatsuya Higashino, Motoharu Osika

7. The Latest Status and the Outlook of Quick Charging

By Kazuya Yoshihara, Utaka Kamishima
◆ New Technology
   By Kazuya Matsuoka, Shinichi Kiga, Shuji Kojima,
   Katsuya Moteki, Eiji Takahashi

◆ New Models
9. Product Overview of the New Nissan LEAF .................................................................. 62
   By Makoto Fukuda

10. Product Overview of the New INFINITI QX50 ............................................................. 67
   By Chiaki Sumi

◆ List of Technical Award Recipients .............................................................................. 72

◆ Technical Award News
11. Magnetization State Manipulation Method with Low Vehicle Vibration for High Speed Operating Region of Variable Flux PMSMs ......................................................... 76
   By Kensuke Sasaki, Brent S. Gasas, Takashi Fukushima,
   Takashi Kato, Kan Akechi, Robert D. Lorenz
自動車大転換期を迎えて-礎となる
新型日産リーフのEV技術

アライアンス グローバル ダイレクター
鳥海 眞樹

2017年は、自動車業界にとってターニングポイントの年と記憶されるだろう。英仏政府が「2040年までにガソリン車やディーゼル車の販売を禁止する」と宣言し、中国では「NEV（新エネルギー）規制を2019年から導入する」と発表するなど、世界中で電動化シフトが明確に打ち出され、自動車業界は100年に一度の大転換期を迎えていると言われている。各自動車会社が次々と電動化やEV（電気自動車）化の計画を発表しているだけでなく、新たに異業種からEVへの参入を表明するなど、まさに異次元の競争展開に突入し、混沌を極めている。

我々ルノー・日産・三菱アライアンスも2022年までに12車種の新たなEVを販売することを発表した。EVの激しい競争に勝つために、ルノー・日産・三菱アライアンスは航続距離を600km以上に伸長し、バッテリのコスト30%低減、15分の充電で航続距離230km回復などの技術を展開に取り組んでいる。またEVリーダーシップを堅持し、未来のEV社会の実現のための先進的な技術の創出に、スピード感を持って挑戦し続けている。

そんな中、日産自動車は、2017年10月に新型日産リーフを市場に送り出した。我々日産は2010年のリーフ発売以来、世界でEV累計販売30万台以上を達成し、お客様の様々な声や、市場のニーズ、EVの使い方に関する膨大なデータを有している。これはEVのバイオニクルである日産ならではの財産であり、それを発展にフィードバックしている。新型日産リーフは、最新のEV用パワートレイン、バッテリと制御技術を搭載し、満を持して発売した。EV用パワートレインは、モータ・インバータの技術進化により高出力・高トルク化し、高い加速性能を実現している。またバッテリは同じ大きさで、室内空間を犠牲にすることなく、大容量のものを持ち売し、2010年当時の2倍に達する400km（JC08）の航続距離を実現している。これらEV用パワートレインの大幅な進化と、新たなEVの走りの魅力向上に貢献した制御技術において、本特集を通じて感じて頂ければと思う。

これら新型日産リーフの技術は、EVの異次元競争時代の礎となる技術である。今回の技術を足掛かりにし、更なる高みを目指し、EVの技術イノベーションに邁進したい。それが地球温暖化などの世界的環境問題やエネルギー政策への寄与、社会的責任を果たせば幸いです。
The year 2017 will likely be remembered as a significant turning point for the automotive industry. The governments of both the U.K. and France stated that sales of gasoline and diesel vehicles will be banned by 2040. China announced that its new energy vehicle (NEV) regulations will be implemented from 2019. These and other announcements have clearly indicated a global shift to electrification, and it is said that the automotive industry is on the verge of a major turning point that occurs once in a hundred years. Not only are vehicle manufacturers revealing one plan after another for electrification and electric vehicles (EVs), companies in other industries are also expressing their intention to enter the EV market. A struggle for leadership on a totally different dimension has suddenly occurred, giving rise to an extremely chaotic situation.

Our Renault-Nissan-Mitsubishi Alliance announced that twelve new EV models will be put on the market by 2020. In order to win the fierce EV competition, the Alliance is developing technologies for extending the driving range to 600 km, reducing the battery cost by 30%, and facilitating 15-minute charging to recover a driving range of 230 km, among other targets. Moreover, to firmly maintain our EV leadership, we are continuing the challenge to create advanced technologies quickly for building a future society centered on EVs.

Against this backdrop, the new Nissan LEAF was released in October 2017. Since rolling out the first-generation Nissan LEAF in 2010, we have achieved cumulative sales of over 300,000 EVs worldwide. We possess an enormous amount of data concerning customers’ various opinions, real-world quality and how EVs are driven. This represents a valuable asset that only Nissan as an EV pioneer could amass, and the information is fed back for use in the development process. The much-awaited new Nissan LEAF is equipped with the latest electric powertrain, battery and control technologies. The electric powertrain delivers higher power and torque for enhanced acceleration performance, thanks to advances made in motor and inverter technologies. While the battery is the same size so as not to sacrifice interior roominess, its capacity has been improved to provide a driving range of 400 km under Japan’s JC08 emission test mode, which is twice that of the initial model in 2010. It is hoped that the special feature in this issue will enable readers to understand the profound evolution of the EV powertrain and the control technologies that contribute to enhancing the novel fascination of driving an EV.

The technologies embodied in the new Nissan LEAF will serve as the technical foundations for the coming era of EV competition on a different dimension. Using the present technologies as a foothold, we intend to move ahead with further EV technological innovation, aiming to attain even greater heights. We will be very happy if we can discharge our social responsibility by contributing to the resolution of global environmental issues like global warming and to the advancement of energy policy.
1. Introduction

Nissan is focusing on the development of technologies for four key social issues with the aim of building a sustainable society. As shown in Fig. 1, these issues are energy depletion, global warming, congestion and traffic accidents. They are prevalent in both industrialized and emerging economy countries.

In order to solve these issues, Nissan has set two major directions, "electrification and intelligence", as its technology development strategy. Figure 2 shows Nissan’s technology development approach in these two areas. Intelligent technologies are evolving in stages toward autonomous driving. Simultaneously, electrification technologies are evolving in stages from a level of adding electrified elements with internal combustion engines (ICEs) toward achieving the ultimate goal of electrification in the form of electric vehicles (EVs). e-POWER is a new electric powertrain concept introduced in 2016 for the

![Fig. 1 Social issues as background of technology development](image1)

![Fig. 2 Key concepts of Nissan technology development](image2)

![Fig. 3 First-generation 2011 MY Nissan LEAF](image3)
2. Evolution of the Electrical Powertrain for EVs

The Nissan LEAF was launched as the first mass-produced EV with a reasonable price in 2010. The Nissan LEAF is a medium-size hatchback that can seat five adults comfortably. This first-generation 2011 model year Nissan LEAF had a driving range of 200 km under Japan’s JC08 emission test mode, sufficient to satisfy real-world consumer requirements for daily use (Fig. 3).

As of September 2017, the cumulative sales volume of the Nissan LEAF surpassed 280,000 units. The Nissan LEAF has maintained its top position in cumulative sales volume in the global EV market as shown in Fig. 4. After Nissan launched the LEAF in 2010, many automotive manufacturers have also launched EVs, making competition in the EV market more intense with every passing year.

In order to keep the Nissan LEAF competitive, the first-generation vehicle underwent a minor model change twice to adopt electric components that evolved during its seven-year model life. In the 1st minor change for the 2013 MY vehicle, high-voltage components were integrated for compactness and weight reduction and the efficiency of the electric motor and inverter was improved while lowering the cost. Improved efficiency also contributed to extending the driving range. In the 2nd minor change for the 2016 MY vehicle, the energy capacity and power density of the Li-ion battery were increased. The battery capacity was increased to 30 kWh while keeping the battery pack the same size as before.

In October 2017, Nissan launched the new Nissan LEAF (Fig. 5). Maximum power and torque of the electric motor were improved to 110 kW and 320 Nm. Li-ion battery capacity was increased to 40 kWh, while keeping

### Table 1: Comparison of Nissan LEAF specifications

<table>
<thead>
<tr>
<th></th>
<th>11MY</th>
<th>13MY</th>
<th>16MY</th>
<th>18MY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. power [kW]</td>
<td>80</td>
<td>80</td>
<td>← 110</td>
<td></td>
</tr>
<tr>
<td>Max. torque [Nm]</td>
<td>280</td>
<td>254</td>
<td>← 320</td>
<td></td>
</tr>
<tr>
<td>Inverter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. current [Arms]</td>
<td>340</td>
<td>282</td>
<td>← 456</td>
<td></td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>16.8</td>
<td>15.3</td>
<td>← 11.4</td>
<td></td>
</tr>
<tr>
<td>Battery</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacity [kWh]</td>
<td>24</td>
<td>24</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Driving range</td>
<td>JC08 (Japan) [km]</td>
<td>200</td>
<td>228</td>
<td>280</td>
</tr>
</tbody>
</table>
The battery pack the same size. The major specifications of the new Nissan LEAF are shown in Table 1 in comparison with those of the previous models.

Figure 6 shows the evolution of each component used in the electric powertrain since the first-generation 2011 MY Nissan LEAF. Electronics and power semiconductor devices evolve quickly. That evolution and new innovations can be used in a timely manner to achieve more compact packaging and further integration for the power electronics components like the inverter, DC/DC converter and on-board charger (OBC). The battery chemistry has also been improved year by year, and this evolution has been applied to improve the battery cell technology. On the other hand, the mechanical interface of the battery and the dimensions of the electric motor stator/rotor have been kept the same, but the materials and inside structure have been changed to improve performance. Because changing the mechanical interface would require capital investment in production facilities, it is desirable to use these assets as long as possible. Nissan plans to introduce a new model with higher performance and a longer driving range, while keeping the components the same size.

3. Evolution of Electric Powertrain Control System

An innovative feature of the new Nissan LEAF is e-Pedal for controlling vehicle deceleration smoothly on various road surface conditions by just operating the accelerator pedal. Running resistance is estimated based on the drive motor torque, and advanced cooperative control of the mechanical brakes and the electric motor is...
性と制御性の良さを最大限に活用したスムーズで早さの加速応答性であり、電動車両技術として10年以上から開発を進めてきた。図8に示すように、電動モータの応答性を大幅に改善するたび、ドライバーシャフトはねじり振動によって大きな振動が発生する。東陽では制御対象をモデル化し、フィードバック制御とフィードフォワード制御による電動モータの応答性の良いスムーズな加速応答性を両立している。さらに、新型車両が上部、下部スムーズさと応答性を損なうことなく駆動性能を大幅に向かしている。スムーズで早さあり加速応答性は運転する楽しさだけではなく、不慣なドライバーにも新規での運転のしやすさを提供することができ、東陽リーフが市場で支持されています理由の一つと言える。

4. まとめ

東陽リーフは2010年のデビュー以来、世界で支持される累計販売台数は世界一の座にあり、その競争力を維持するための技術改良を行ってきている。満を持して、2017年にフルモデルチェンジの新型リーフがデビューし、第一世代に続いて多くの支持を集めている。東陽は100%モータ駆動の電動車の魅力を電動化のコアバリューとして推進していく。

5. 参考文献


日産電気自動車用パワートレインの進化

used to stop vehicle extremely smoothly even on steep grades and to hold it in that condition (Fig. 7).

One of the distinctive features of Nissan EVs is smooth, responsive acceleration obtained by using the excellent response and controllability of the electric motor. The motor has been developed and refined for over 10 years as a core EV technology. As Fig. 8 shows, simply quickening motor responsiveness causes large vibration due to torsional resonance of the drive shaft. Nissan has developed a shaking vibration control system using feedforward and feedback controllers based on a control model, which achieves both smooth and quick response. The new Nissan LEAF delivers higher power performance without sacrificing this smooth and quick response. This controllability of the electric powertrain not only provides driving pleasure, but also driving ease in daily use for inexperienced drivers. This is one reason why the Nissan LEAF has been so popular in the global market.

4. Conclusion

The Nissan LEAF has kept the top position in cumulative sales in the global EV market since the first-generation model was launched in 2010. The electric powertrain has continuously been improved to maintain competitiveness. In 2017, the new Nissan LEAF debuted after a full model change. It has attracted a lot of customers just like the first-generation LEAF. Nissan is promoting the fascination of all-electric-drive vehicles as one of the core values of electrification.

5. References

Evolution of Electric Powertrain for Nissan Electric Vehicle

Author(s)

Taiichi Onoyama
Kantaro Yoshimoto
1. Introduction

The Nissan LEAF was released in 2010 as the world’s first mass-produced electric vehicle. Its cumulative sales volume has surpassed 280,000 units, making the Nissan LEAF the most driven EV worldwide. The Nissan LEAF has won numerous awards, including having its electrified powertrain selected by Ward’s AutoWorld magazine in the U.S. for Ward’s 10 Best Engines list in 2011, the first such powertrain ever to be given this distinguished honor.

Summary

This article describes a newly developed motor and inverter system with maximum torque of 320 Nm and maximum power of 110 kW for the new Nissan LEAF electric vehicle. The system achieves this performance with no increase in size over the previous system with maximum torque of 254 Nm and maximum power of 80 kW. This performance improvement has been achieved with a new inverter power module that adopts a direct cooling structure, motor magnets with reduced heavy rare earth elements, and controls that optimally manage the motor voltage and the temperatures of the power semiconductors and motor.

Key words: Power Unit, electric vehicle (EV), motor, interior permanent magnet synchronous motor, motor drive system, inverter, power module

2. システム概要

図1に新型日産リーフ用電動パワートレインの外観及び車両プラットフォームを、図2に電動パワートレインのエネルギの流れを示す。電動パワートレインは、前型モデルと同様、車両前方のモータールームに搭載されている。
The motor and inverter system of the electrified powertrain used on the new Nissan LEAF has been downsized and reduced in weight compared with that of the previous model. This enables the new Nissan LEAF to achieve further performance improvements for enhancing its powerful, high-quality driving capabilities that typify a motor-drive system.

This article outlines the motor and inverter system used on the new Nissan LEAF and describes the technologies adopted for improving performance, focusing mainly on the changes made from the previous model.

2. System Overview

Figure 1 shows the appearance of the new Nissan LEAF’s electrified powertrain along with the vehicle platform. The energy flow in the electrified powertrain is shown in Fig. 2. Like the previous model, the electrified powertrain is mounted in the motor compartment at the vehicle front. Consisting of four modularized parts, the overall electrified powertrain has a compact structure that is mechanically and electrically integrated. The drive motor serves as the vehicle’s power source. The inverter supplies and controls the electric energy provided from the battery to the motor. The Power Delivery Module (PDM) consists of the charger, DC/DC converter and the junction box. The reducer transfers the driving force produced by the motor to the drive shaft and tires.

The appearance of the motor and inverter system for the new Nissan LEAF and the system specifications are shown in Fig. 3 and Table 1, respectively, in comparison with the system used on the previous model. The maximum power of the system has been improved from 80 kW to 110 kW and the maximum torque from 254 Nm to 320 Nm.
同じくIPMSM（Interior Permanent Magnet Synchronous Motor）タイプを採用し、高い出力性能を有している。

図4に新型日産リーフのモータトルク及び出力特性を、前型モデルと比較して示す。インバータ内部のパワーモジュールの改良、及びパワーモジュールとモータの温度保護制御ロジックの最適化により、モータ回転数0rpmから最大トルク320Nmを発揮することができるモータ&インバータシステムとなっている。さらに、モータ電圧マネジメントを最適化することで、最大出力110kWが可能となっている。

0rpmから最大トルクが発揮できること、及び前型モデルでも適用していた常振動制御技術（駆動力伝達系のねじり振動を抑制しつつ迅速かつスムーズな応答を実現する制御）によって、図5の全開加速時の応答に示すように、他車両と比較し振動のない高速的な応答を可能にしている。

図6に各モータの回転数、及びトルクに対するモータ&インバータシステムの効率を、前型モデルと比較して示す。

The interfaces of the motor and inverter system on the new Nissan LEAF with the PDM and with the reducer have the same geometries as those of the previous model in order to facilitate the use of existing production facilities and reduce part costs.

The mass and volume of the inverter have been reduced by downsizing and lightening its internal components, which helps to improve electric power consumption. The motor, inverter and PDM are directly connected by busbars to facilitate exchanges of electric energy among them, thereby forming an integrated structure. Heat generated by electric losses occurring in the system is evacuated outside the system by coolant flowing through internal channels. Like that of the previous model, the motor is an interior permanent magnet synchronous motor (IPMSM) that provides high power performance.

Figure 4 compares the motor torque and power characteristics of the new Nissan LEAF and the previous model. The motor and inverter system can deliver its maximum torque of 320 Nm from a motor speed of 0 rpm, as a result of improving the power module in the inverter and optimizing the thermal protection control logic for the power module and motor. In addition, optimization of motor voltage management enables the system to provide maximum power of 110 kW.

The ability to deliver maximum torque from 0 rpm and a shaking vibration control system enable the new Nissan LEAF to provide fast acceleration response without any hesitation compared with other vehicles, as indicated by the response characteristics under full-throttle acceleration.
shown in Fig. 5. The vibration control system was also adopted on the previous model and serves to suppress torsional vibration in the drive train system for achieving quick and smooth vehicle response.

The efficiency of the new and previous motor and inverter systems is shown in Fig. 6 in terms of the motor speed and torque of each motor. Efficiency has been improved over the previous model especially in the high-speed region by optimizing power module switching operations and motor voltage management.

3. Inverter

The flow of electric energy in the inverter was shown earlier in Fig. 2. Energy from the battery is stored in a smoothing capacitor that regulates the supply of energy to the motor according to the turn-on/turn-off switching operations of the power semiconductors in the power module. The control signal issued by the motor controller in the inverter is amplified by the gate drive circuit to control the switching operations of the power module. This contributes to the output performance of the inverter. The following technologies were adopted for the inverter this time to improve performance.

3.1 Higher motor torque

The output current of the inverter must be increased in order for the motor to generate higher torque. That requires improvement of the heat radiation performance and reduction of the electrical losses when current is conducted.

The power module adopts a new structure that improves heat radiation. Table 2 compares the structure of the power modules used on the new Nissan LEAF and the previous model. As the cross-sectional view of the structure indicates, the power module adopted on the previous model did not have any internal electrical insulation. The power module adopted on the new Nissan LEAF is insulated internally and has a directly cooled structure that also integrates the coolant fins. This eliminated the need for the insulation sheet and grease used between the module and the radiator on the previous model. As a result, the power module can be mounted directly on the inverter case as shown in Fig. 7. However, because there are seal interfaces with the coolant channels inside the inverter, the module structure has been designed to ensure satisfactory performance.
sealing performance even after aging in order to meet identified market requirements. This has made possible large current conduction while still reducing the size of the power module by approximately 50% compared with that of the previous model.

Figure 8 compares the appearance of the smoothing capacitors used on the new Nissan LEAF and the previous model. Inductance between the smoothing capacitor and the power module, which influences the losses and surge voltage of the latter device, has been reduced by 40% from that of the previous model. This was accomplished by expanding the laminated area of the P- and N-phase busbars, based on a layout optimization study, and by downsizing the capacitor by approximately 20% by applying thinner films.

Optimization of the gate drive circuit also contributed to reducing power module losses. The trade-off between losses that occur during turn-on/turn-off switching operations and surge voltage, i.e., voltage overshoot, was evaluated by comprehensively varying the electrical characteristics of the power module. The gate drive circuit design was determined on that basis. As a result, power module losses were reduced by approximately 14% compared with the previous model.

Thermal protection logic was adopted for the power semiconductor chips used on the new Nissan LEAF. This logic uses the power module temperature measured with a thermistor on the power module substrate and the coolant temperature measured with a sensor installed at the coolant channel inlet of the inverter. The temperature of the power semiconductor chips, which are subject to severe temperature restrictions, was measured using an infrared (IR) camera as shown in Fig. 9 during experimental inverter switching operations under an applied motor load. The correlation between the power semiconductor chip temperature and the thermistor sensor value under each operating condition was found and used to determine the thermal protection specification for a condition of high current conduction.

3.2 Higher motor output

In order to increase the motor output, it is necessary to apply voltage to the motor that is higher than

<table>
<thead>
<tr>
<th>Motor voltage management comparison</th>
<th>Previous model</th>
<th>New Nissan LEAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal peak modulation ratio</td>
<td>0.7 – 0.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 3 Comparison of motor voltage management
インバータのモータ制御ソフトウェアでは、表3に示すように、新型日産リーフはモータ電圧マネジメントを最適化し、変調率（インバータの入力電圧に対するモータへの出力電圧の利用率）1.0まで使うことができている。これは前型モデルの実績から、モータ磁石特性の温度依存性を考慮し、その磁石特性変化の影響を分析・検証することによって実現されており、この点が高出力化と高効率化に貢献している。

4. モータ

図10に新型日産リーフのモータ部品の分解図を示す。既存の設備の活用を目的に、基本構成は前型モデルから変更なく、ロータコアにはネオジム磁石、ステータコアは低損損化のために薄板化された積層電磁鋼板、回転位置センサはレゾルバを採用している。

4.1 省資源化

ロータコアで使用しているネオジム磁石には、高温下での保持力を確保するために希少元素である重希土（ジスプロシウム（Dy）など）を添加している。新型日産リーフでは図11に示すように、磁石粒子サイズを微細化するとともに重希土を磁石粒子界面のみに拡散させている。これにより耐熱性能を向上させ、重希土使用量の削減、つまりは省資源化を実現している。

4.2 高トルク化

新型日産リーフでは車両の新機能として、アクセルペダルのみによる発進、加減速、停止を可能とする車両制御e-Pedalが採用された。この新機能により低速でのモータの使用頻度の増加が想定され、また高トルク化のため大電流通電が必要となる。そのため、モータコイルの温度保護として新たな保護方式を探用した。通電時にコイル温度上
5. Conclusion

The motor and inverter system newly developed for powering the new 2018 model year Nissan LEAF produces maximum power of 110 kW and maximum torque of 320 Nm and incorporates the following major features.

1. A new power module with a directly cooled structure and control logic for optimally managing the temperatures of the power semiconductors and the motor contribute to the attainment of higher torque.

2. The motor core made of thin laminated electromagnetic steel sheet and optimized motor voltage management contribute to higher power performance and efficiency.

3. Reduction of the quantity of heavy rare earth elements added to the magnets contributes to resource savings.

These features and the development of motor control logic matching the power module and motor characteristics bring out the maximum performance of the motor and inverter system. This makes it possible to provide customers with powerful performance and a unique driving feel that only an EV can deliver.

We will continue to develop this system with the aim of achieving even higher torque and power performance so as to meet market requirements in the years ahead.

6. Acknowledgments

The authors express their deep appreciation for the invaluable cooperation received from wide-ranging quarters to achieve the high performance and quality required of the motor and inverter system. Thanks are especially due the suppliers of the system components and naturally the related departments in Nissan’s Research and Development Division as well as others outside this division, including the Manufacturing Division and Procurement Division.

![Battery Inverter Motor](image)

**Fig. 12** Schematic diagram of the thermal protection logic of the motor coil

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Fig. 11 Reduction of rare earth elements for motor magnets
7. 参考文献


7. References

新型日産リーフの電動パワートレイン制御システム

Electric Powertrain Control System for the New Nissan LEAF

Yoshinori Seki† Takahisa Kurosawa‡ Kantaro Yoshimoto† Seishi Shimamura

Summary

The new Nissan LEAF features a new powertrain that maintains the quiet, smooth, and responsive acceleration performance characteristic of Nissan EVs, while improving the vehicle’s power performance and driving range. We have also newly developed e-Pedal that combines braking control with the e-POWER Drive mode incorporated in the fully motor driven e-POWER electric powertrain adopted on the 2017 Note e-POWER. e-Pedal enables the vehicle to be accelerated, decelerated and stopped on many roads by accelerator pedal inputs alone in cooperation with braking control. The new Nissan LEAF achieves a driving range of 400 km in the JC08 mode as a result of improving the efficiency of the motor/inverter, enhancing the system control and installing a large-capacity battery.

Key words: Power Unit, Performance, Electronics, power train, electric vehicle (EV)

1. Introduction

The Nissan LEAF has proposed smooth and highly responsive driving performance as attractive characteristics of motor drive, since the first-generation model was released in 2010 as the world’s first mass-market electric vehicle (EV). The driving range of the Nissan LEAF was extended in two minor model changes by improving driving force control and increasing the capacity of the high-voltage battery.

The new Nissan LEAF is equipped with an electric powertrain that continues the attractiveness of motor drive, which is a compelling feature of Nissan EVs, and also

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図-1 電動パワートレインの概要

Fig.1 Configuration of the electric powertrain
Electric Powertrain Control System for the New Nissan LEAF

ギネというバッテリで構成している。コンポーネントはサイズを従来以下とし、大幅に性能を向上させている。そのためプラットフォームの大きな変更を行わず、車両への搭載を可能とした。

2.2 コンポーネント

コンポーネントの構成を表1に示す。駆動モータは従来型と同じサイズで、図2に示すように最大出力は35%、最大トルクを25%向上している。インバータは小型で駆動系を実現しながら、冷却性能を強化した最大出力、制御改良によりモータの出力とトルクを向上させている。

バッテリは従来型と同様にリチウムイオンバッテリを踏襲しているが、セルを新設計することでバッテリの大きさをそのままに電池容量を約30%向上させ、モータ出力向上に伴い最大出力も約14%向上させた。

3. 車両性能

3.1 動力性能

発進加速性能と中間加速性能を図3に示す。発進時のGは従来型を大きく上回り、中間加速のシーンでも力強さは確保されている。

3.2 運転性

ノート e-POWERではモータの特性を生かして、多く

<table>
<thead>
<tr>
<th>Component</th>
<th>Previous model</th>
<th>New Nissan LEAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>Max. power</td>
<td>80 kW</td>
</tr>
<tr>
<td></td>
<td>Max. torque</td>
<td>254 Nm</td>
</tr>
<tr>
<td>Inverter</td>
<td>Mass</td>
<td>15.3 kg</td>
</tr>
<tr>
<td></td>
<td>Volume</td>
<td>13 L</td>
</tr>
<tr>
<td>Battery</td>
<td>Capacity</td>
<td>30 kWh</td>
</tr>
</tbody>
</table>

substantially improves the vehicle’s power performance and driving range.

This article outlines the new electric powertrain system used on the new Nissan LEAF, describing its performance and presenting an overview of its control system.

2. Powertrain System

2.1 System configuration

The configuration of the new electric powertrain system is shown schematically in Fig. 1. The system consists of a drive motor for propelling the vehicle, an inverter, a reducer, a power delivery module (PDM) that integrates a junction box, a DC/DC converter and a charger, and a battery as the energy source. While the components are smaller in size than their counterparts on the previous model, their performance has been greatly improved. Consequently, they have been installed on the vehicle without making any major changes to the platform.

2.2 Component specifications

The specifications of the main powertrain components are listed in Table 1 in comparison with those of the previous model. While the drive motor is the same size as that of the previous model, its maximum power has
の加減速シーンをモータトルクでコントロールするe-POWER Driveを採用した。新型日産リーフでは、e-POWER Driveを更に進化させてブレーキ制御と協調させてe-Pedalを開発した。

e-Pedalはe-POWER Driveをブレーキ制御と協調させることで厳しい条件での車両停止や、ブレーキによる車両の保持、例えば急な勾配で車両をスムーズに停止させ、その状態を維持することが可能である。また、長い下り坂のようなバッテリー満充電状態においても、ブレーキと協調することでコスト減速Gを補償させ、市場における走行速度の約90%をアクセル操作だけで運転可能とした。

従来、アクセルペダルを緩めて停止を行う際は、路面の勾配に応じてモータトルクを切り合わせて滑らかに車両を停止させていたが、急な勾配での停止中は大きなモータトルクの保持が必要となりモータ＆インバータシステムの冷却性能を大幅に強化する必要があった。e-Pedalはブレーキ制御との協調により、停止中はブレーキの摩擦制動力で停止を維持させることができるモータ＆インバータシステムの発熱を抑制させている。

また、従来は長い下り坂でバッテリー充電が続き満充電状態になるとモータ回生が制限されるため、モータによるコスト減速Gが制限されていた。e-Pedalではブレーキを協調制御することでコスト減速Gを補償し、アクセルペダルのみの操作であらゆるシーンでの車両コントロールを可能とした。

図4にe-Pedalの機能ブロック図を示す。e-POWER Driveでは車速とアクセル開度によってドライバの要因駆動力を決定しモータトルクを指令していたが、e-Pedalモード切替時にはスムーズな制動を行うため、ドライバの要求駆動力を常にモータトルクと摩擦ブレーキ制動力に分配する構成にしている。さらにe-POWER Driveと同様に、勾配などの路面の負荷消除を含めてモータトルクを補正することによりブレーキと協調させて、市場で最も厳しい条件である30%の急勾配でもアクセルペダル操作のみでスムーズな停止、発進を可能とした。

![function block diagram](image)

図4 機能ブロック図

Fig. 4 Function block diagram

被験物の電動パワートレイン制御システム

新型日産リーフの電動パワートレイン制御システム

被験物の電動パワートレイン制御システム

新型日産リーフの電動パワートレイン制御システム

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新型日産リーフの電動パワートレイン制御システム

新型日産リーフの電動パワートレイン制御システム

The available coasting deceleration G. Because of the cooperative control between e-Pedal and the braking system, coasting deceleration G is compensated, making longitudinal vehicle control possible in many situations through accelerator pedal inputs alone.

A function block diagram of e-Pedal is shown in Fig. 4. With e-POWER Drive, the driving force demanded by the driver is determined on the basis of the vehicle speed and the accelerator pedal angle, and a motor torque command is issued. However, when the e-Pedal mode is selected, the driver’s requested driving force is constantly distributed between the motor torque and friction braking force so as to ensure smooth braking action. Moreover, similar to e-POWER Drive, motor torque is compensated according to the road load such as the road grade. In addition, by working in concert with the braking system, e-Pedal makes it possible to stop and launch the vehicle smoothly by accelerator pedal inputs alone on a steep 30% road grade, which is one of the severest conditions in real-world driving.

Figure 5 presents data for cooperative braking by motor torque and the mechanical braking system during coasting deceleration in the e-Pedal mode under a condition where regenerative motor torque is limited by the high state of charge of the battery. When the e-Pedal mode is selected, the driver’s requested driving force is distributed between the motor torque and the braking
force of the friction braking system. Consequently, the friction braking force can sustain the coasting deceleration G, enabling longitudinal vehicle control at all times by accelerator pedal inputs alone.

Figure 6 presents data for stopping and launching the vehicle in the e-Pedal mode on a 30% uphill grade. The system assumes a steep uphill grade and smoothly controls the motor torque and friction braking force in concert to facilitate the vehicle launch on the steep slope. For stopping the vehicle, on the other hand, the motor torque is used to stop the vehicle smoothly. After the vehicle is stopped, the work done by the motor torque is transferred to the friction braking force to hold the stopped vehicle. This cooperative action prevents the temperature of the motor and inverter system from rising and facilitates stable stopping of the vehicle.

3.3 Driving range

The cell arrangement of the battery used on the new Nissan LEAF continues that of the previous model with 96 cells connected in series in two rows. The capacity per cell was improved to attain a battery capacity of 40 kWh, enabling the new Nissan LEAF to achieve a driving range of 400 km (Fig. 7).

Moreover, the efficiency of the motor and inverter system was improved by reducing iron losses through
4. まとめ

新型日産リーフでは、日産EVの特長であるスムーズでレスポンスの良い加速を維持したまま、電動パワートレインのトルク、出力の向上により力強い加速を実現した。また、2016年に発売したノートe-POWERで採用したe-POWER Driveにブレーキ制御と協調させる改良を加えたことにより、アクセル操作のみであらゆるシーンでの運転を可能とするe-Pedalを開発した。

さらに、大容量バッテリ、電動パワートレインの高効率化、実用走行時のモータ出力損失の低減などによりJC08モード400kmの航続距離を達成した。

4. Conclusion

The new Nissan LEAF provides powerful acceleration owing to the improved torque and power of the electric powertrain while continuing the smooth, responsive acceleration performance that is a distinctive feature of Nissan EVs. It also adopts e-Pedal that enables longitudinal vehicle control in various driving situations by means of accelerator pedal inputs alone. e-Pedal was developed by further improving cooperative control with the braking system in the e-POWER Drive mode incorporated in the e-POWER electric powertrain used on the Nissan Note released in 2016.

In addition, the driving range of the new Nissan LEAF was extended to 400 km under Japan’s JC08 emission test mode. That was accomplished by adopting a material change to a low-loss electromagnetic steel sheet and by reducing power module switching losses as a result of increasing the gate drive speed. System control incorporates coasting deceleration G that efficiently recovers regenerative energy during vehicle deceleration.

Figure 8 compares the characteristics of coasting deceleration G in the Eco mode between the previous and new models. Previously, coasting deceleration G was designed in reference to that of an engine-mounted vehicle. However, the friction braking system produced losses in cooperative action with motor regenerative deceleration when the brake pedal was operated in the low and intermediate speed ranges. In order to reduce such losses, deceleration G due to regenerative motor torque was expanded to reduce the frequency of using the friction braking system, which contributed to extending the driving range. In the high-speed range, on the other hand, because the frequency of depressing the brake pedal is low, coasting deceleration G was weakened to reduce motor losses caused by unnecessary acceleration and deceleration.

In situations involving cruising at intermediate to high speeds, unnecessary acceleration/deceleration previously occurred due to the driver’s slight operation of the accelerator pedal, which increased motor losses. To reduce such losses, the new Nissan LEAF also adopts a gliding control feature like that included in the e-POWER system on the Nissan Note.

Figure 9 shows the driving force distribution on a suburban road in Japan. It is seen that the driver is unconsciously accelerating/decelerating the vehicle slightly while cruising. Because this repetition of slight acceleration/deceleration occurs in the region of low motor efficiency, the increase in motor losses cannot be ignored. Figure 10 shows the configuration of the gliding control that was adopted to improve this situation. Like the Note’s e-POWER system, the driver’s slight accelerator pedal inputs are cancelled in the vicinity of the driving force needed for cruising according to the vehicle speed, thereby reducing motor losses (Fig. 11). This gliding control improves the practical driving range of the new Nissan LEAF by approximately 6%.
5. References


a high-capacity battery, improving the efficiency of the electric powertrain, and reducing motor power losses in the practical driving range, among other improvements.
1. Introduction

The e-Pedal function newly adopted on the new Nissan LEAF all-electric vehicle (EV) enables the driver to accelerate, decelerate and stop the vehicle by operating just the accelerator pedal. It helps to lighten the driver’s operational workload by reducing the frequency of switching the foot to depress the brake pedal. This function is especially effective in situations involving repeated acceleration, deceleration and stopping due to surrounding traffic conditions, actions that are typical of city driving.

Because acceleration and deceleration are accomplished by the drive motor with this function, situations frequently occur in which there is a reversal of direction between drive torque and regenerative torque.

Key words: Electronics, Vibration, electric vehicle (EV), electric motor, electronic control, gear backlash

1. はじめに

100%電気自動車（EV）の新型日産リーフに新たに採用した「e-Pedal」は、アクセルペダル操作のみで発進、加速、減速、停止ができる機能である。ブレーキペダルの踏み替え操作を減らすことにより、ドライバの運転操作負担を低減することができる。特に市街地などで、周囲の状況に応じて加減速と停止を繰り返すシーンにおいて有効である。

この機能は、駆動モータによって加減速を行うため、力行トルクと回生トルクが切り替わるシーンが頻繁に発生する。その際に生じるギヤホイールの衝撃が、駆動軸ねじり振動を発生し、車両前後振動が発生する。前型モデルの駆動軸ねじり振動制御は、モータの逆応答なレスポンスを抑えることなく、駆動軸ねじり振動を抑制する技術であるが、上記のシーンにおいてわずかに振動が残るという課題があった。そこで私たちはe-Pedalの滑らかな加減速を実現するために、駆動軸ねじり振動制御の更なる性能向上に取り組んだ。

本稿では、ギヤバックラッシュによる振動を抑制し、滑らかな加減速を実現する新たな駆動軸ねじり振動制御技術を紹介する。

Key words: Electronics, Vibration, electric vehicle (EV), electric motor, electronic control, gear backlash

1. 摘要

When driving in the e-Pedal mode, the drive motor generates powerful regenerative torque and the direction of motor torque frequently changes. Drive shaft torsional vibration is induced by the impact of gear backlash that occurs when motor torque reverses direction. A new method has been developed for controlling drive shaft torsional vibration to secure smooth acceleration and deceleration.

Key words: Electronics, Vibration, electric vehicle (EV), electric motor, electronic control, gear backlash

Fig. 1 駆動系システム構成

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2. 駆動系システム構成

新型日産リーフの駆動系システム構成を図1に示す。駆動モータは埋込磁石同期モータ(IPMSM)を採用しており、車両制御モジュールは、アクセル開度、車速、リチウムイオンパッテリの状態など、車両の状態によってモータトルク指令値を決定する。モータコントローラは、車両制御モジュールからのモータトルク指令値に従ってパワー制御スを介してモータトルクを制御しており、駆動軸ねじり振動制御はモータコントローラ内に実装されている。

3. 制御システム

3.1 車両モデル

駆動軸ねじり振動制御システムを導出するために、EVの駆動トルク伝達系を図2、車体の前後運動を図3のよう
にモデル化する。図2、図3に示される車両の運動方程式
は、(1)式のように表される。

\[
\begin{align*}
J_m \frac{d}{dt} \omega_m &= T_m - T_d \frac{T_d}{N} \\
2J_c \frac{d}{dt} \omega_c &= T_d - rF \\
M \frac{d}{dt} V &= F \\
T_d &= K_d \theta_d \\
F &= K_v(\rho \omega_m - V) \\
\theta_d &= \int \left( \frac{\omega_m}{N} - \omega_m \right) dt
\end{align*}
\]

各パラメータは以下の通りである。

- \( J_m \): モータインナーシャ
- \( J_c \): 駆動軸インナーシャ（1軸分）
- \( M \): 従動軸インナーシャを含む車両等価質量
- \( K_d \): ドライブシャフトのねじり剛性
- \( K_v \): タイヤと路面摩擦に関する係数
- \( N \): オーバーオールギヤ比
- \( r \): タイヤ荷重半径
- \( T_m \): モータトルク
- \( T_d \): 駆動軸トルク
- \( F \): 駆動力
- \( \omega_m \): 駆動軸角速度
- \( V \): 車体速度
- \( \theta_d \): 駆動軸ねじり角度

(1) 式の運動方程式から、モータトルク \( T_m \) を入力、モー
tar角速度 \( \omega_m \) を出力とする伝達特性 \( G_m(s) \) は、(2) 式、(3) 式のよう
に求められる。

The impact of gear tooth contact occurring at that time induces torsional vibration in the drive shaft, giving rising to vehicle longitudinal vibration. The drive shaft torsional vibration control technique used on the previous LEAF model suppressed such vibration without sacrificing the high responsiveness of the drive motor, but there was an issue that slight vibration remained in situations where torque reversed directions. Therefore, we endeavored to improve further the performance for controlling drive shaft torsional vibration in order to secure smooth acceleration/deceleration with e-Pedal.

This article describes a new method for controlling drive shaft torsional vibration in order to ensure smooth acceleration/deceleration by suppressing vibration due to gear backlash.

2. Configuration of Drivetrain System

Figure 1 shows the configuration of the drivetrain system used on the new Nissan LEAF. As the drive motor, the vehicle is equipped with an interior permanent magnet synchronous motor (IPMSM). The vehicle control module determines the motor torque command value according to the vehicle state, including the accelerator pedal angle, vehicle speed, state of charge of the lithium-ion battery and other conditions. The motor controller controls the motor torque via the power device according to the motor torque command value received from the vehicle control module. The drive shaft torsional vibration control system is incorporated in the motor controller.

3. Control System

3.1 Vehicle model

Figures 2 and 3 respectively show the models of the drive torque transmission system of an EV and the
drive axle. The impact of gear tooth contact occurring at that time induces torsional vibration in the drive shaft, giving rising to vehicle longitudinal vibration. The drive shaft torsional vibration control technique used on the previous LEAF model suppressed such vibration without sacrificing the high responsiveness of the drive motor, but there was an issue that slight vibration remained in situations where torque reversed directions. Therefore, we endeavored to improve further the performance for controlling drive shaft torsional vibration in order to secure smooth acceleration/deceleration with e-Pedal.

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\[ \omega_m = G_p(s)T_m \]  
(2)

\[ G_p(s) = \frac{1}{s} \frac{\beta_3 s^3 + \beta_2 s^2 + \beta_1 s + \beta_0}{\alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0} \]  
(3)

The parameters are defined as follows:

\( J_m \): motor inertia
\( J_w \): inertia of one drive wheel
\( M \): vehicle equivalent mass including driven wheel inertia
\( K_d \): torsional rigidity of drive shaft
\( K_f \): coefficient for tire-road surface friction
\( N \): overall gear ratio
\( r \): radius of tire load
\( T_m \): motor torque
\( T_d \): drive shaft torque
\( F \): driving force
\( \omega_w \): angular velocity of drive wheels
\( V \): vehicle body velocity
\( \theta_d \): drive shaft torsional angle

Based on the equations of motion in Eq. (1), the transfer function \( G_p(s) \) consisting of \( T_m \) as the input and the motor angular velocity \( \omega_m \) as the output are found with the following Eqs. (2) and (3).

\[ \omega_m = G_p(s)T_m \]  
(2)

\[ G_p(s) = \frac{1}{s} \frac{\beta_3 s^3 + \beta_2 s^2 + \beta_1 s + \beta_0}{\alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0} \]  
(3)

The constants are defined as follows:

\( \alpha_3 = 2J_m l_m M \)
\( \alpha_2 = K_f l_m (2J_m + r^2 M) \)
\( \alpha_1 = K_f M (J_m + 2J_w / N^2) \)
\( \alpha_0 = K_f K_r (J_m + 2J_w / N^2 + r^2 M / N^2) \)
\( \beta_3 = 2J_w M \)
\( \beta_2 = K_f (2J_w + r^2 M) \)
\( \beta_1 = K_f M \)
\( \beta_0 = K_f K_r \)

Next, Eq. (3) is reorganized to obtain Eq. (4) expressed as:
モータ制御によるバックラッシュ振動の抑制

（1）式の運動方程式から、モータトルク \( T_m \) を入力、駆動軸トルク \( T_d \) を出力とする伝達特性 \( G_t(s) \) は、（5）式、（6）式のように求められる。

\[
T_d = G_t(s) T_m
\]

\[
G_t(s) = \frac{\gamma_1 s + \gamma_0}{\alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0}
\]

各定数は以下の通りである。

\[
\gamma_1 = 2K_d I_d M/N
\]

\[
\gamma_0 = K_d R (2I_d + r^2 M) / N
\]

次に、（6）式を整理して（7）式のように表す。

\[
G_t(s) = \frac{\gamma_1 s + \gamma_0}{\alpha_3 (s + a)(s^2 + 2\omega_0 s + \omega_0^2)}
\]

（7）式の極と零点を調べると、\( a \approx \gamma_0 / \gamma_1 \) となるため、駆動軸トルクの伝達特性は近似的に（8）式で表される。

\[
G_t(s) \approx \frac{g_t}{s^2 + 2\omega_0 s + \omega_0^2}
\]

ここで、

\[
g_t = \gamma_0 / (\alpha_3 a)
\]

入力モータトルク \( T_m \) から駆動軸トルク \( T_d \) に微分ゲイン \( D \) を乗算した値を減算すると、（9）式となる。

\[
T_d = \frac{g_t}{s^2 + 2\omega_0 s + \omega_0^2} (T_m - D \Delta T_d)
\]

（9）式を整理して（10）式のように表す。

\[
T_d = \frac{g_t}{s^2 + 2\omega_0 s + \omega_0^2} T_m
\]

また、ゲイン \( D \) を（11）式とすることにより、駆動軸トルクの伝達特性の減衰係数が1になるため、駆動軸ねじり振動を抑制することができる。

\[
D = 2(1 - \gamma_0) / g_t
\]

また、駆動軸トルクのバックラッシュ特性を不感帯でモデル化すると、（12）式、図6で表される。\( \theta_{\text{ideal}} \) はモータから駆動軸までのバックラッシュ量の合計値である。フィードフォワード補償器内の車両モデルにバックラッシュ（不感帯）特性を考慮することにより、バックラッシュに起因する駆動軸ねじり振動を抑制するフィードフォワードトルク指令値を算出することができる。

\[
T_d = \left\{ \begin{aligned}
K_d \left( \theta_d - \frac{\theta_{\text{ideal}}}{2} \right)
& \quad \left( \theta_d \geq \frac{\theta_{\text{ideal}}}{2} \right) \\
0
& \quad \left( \frac{\theta_{\text{ideal}}}{2} < \theta_d < -\frac{\theta_{\text{ideal}}}{2} \right) \\
K_d \left( \theta_d + \frac{\theta_{\text{ideal}}}{2} \right)
& \quad \left( \theta_d \leq -\frac{\theta_{\text{ideal}}}{2} \right)
\end{aligned} \right.
\]

\[
G_t(s) = \frac{\beta_3 s^3 + \beta_2 s^2 + \beta_1 s + \beta_0}{\alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0}
\]

モータの角速度 \( \omega_m \) はFig. 4の发电机速度に対するモータトルク \( T_m \) の伝達特性を用いて求められる。モータの角速度 \( \omega_m \) は\( \beta_3 s^3 + \beta_2 s^2 + \beta_1 s + \beta_0 \) と\( \alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0 \)の比で算出される。

3.2 Configuration of drive shaft torsional vibration control system

As shown in the block diagram in Fig. 5, the system for controlling drive shaft torsional vibration consists of a feedforward compensator and a feedback compensator.

3.2.1 Feedforward compensator

The feedforward compensator calculates the feedforward torque command value \( T_{f\theta} \) by subtracting from the torque command value \( T_e \) the value obtained by multiplying by gain \( D \) the derivative of the estimated drive shaft torque value \( T_{\hat{\theta}} \) calculated by the vehicle model. The vehicle model also calculates the reference response \( \omega_i \) of the motor angular velocity \( \omega_m \).

Based on the equations of motion in Eq. (1), the transfer function \( G_t(s) \) consisting of the motor torque \( T_m \) as the input and the drive shaft torque \( T_d \) as the output are found with Eqs. (5) and (6), respectively.

\[
T_d = G_t(s) T_m
\]

\[
G_t(s) = \frac{\alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0}{\alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0}
\]

![Fig. 5 Drive shaft torsional vibration control system](image-url)

![Fig. 6 Backlash characteristic of drive shaft torque](image-url)
3.2.2 フィードバック補償器

前節のフィードフォワード補償器を適用することにより、理論上は駆動軸ねじり振動を抑制することができるが、実際の車両においては、モデル化誤差、路面からの外力などの影響（以下、これらを総称して外乱と記す）によって十分な制御性能が得られない場合がある。そこで、外乱の影響を除去する目的でフィードバック補償器を併用する。

図5に示されるフィードバック補償器に用いられる$H(s)$はパルスフィルタであり、(13)式のように中心周波数を制御対象の固有振動周波数$\omega_p$に一致させている。

$$H(s) = \frac{2(1-\zeta_p)\omega_p s}{s^2 + 2\zeta_p\omega_p s + \omega_p^2} \quad (13)$$

図5の制御系において、(2)式、(4)式から外乱$\delta$に対する$\omega_m$の応答を導くと、(14)式のように共振特性を持たない応答となる。

$$\omega_m = \frac{1}{s} \frac{\beta_3 s^3 + \beta_2 s^2 + \beta_1 s + \beta_0}{a_3(s + a)(s^2 + 2\omega_p s + \omega_p^2)} d \quad (14)$$

フィードバック補償器の有無による周波数特性の比較結果を図7に示す。

4. 車両試験結果

車速約10km/hで走行中に回生トルクにより減速し、アクセル操作により再加速した場合の車両応答を図8に示す。この走行条件は、減速している車線をe-Pedalモードで走行中にアクセルで加減速を行うシーンを想定している。

従来のフィードフォワード補償器にバックラッシュ特性を考慮しない制御の場合、駆動軸トルクがオーバーシュートするDanger

図-7 フィードバック補償を施した周波数応答特性
Fig. 7 Frequency response of the new Nissan LEAF with/without feedback control

The constants are defined as follows:

$$\gamma_1 = 2K_d I_m M/N$$
$$\gamma_2 = K_i K_d (2J_w + r^2 M)/N$$

Next, Eq. (6) is rearranged to obtain Eq. (7) expressed as:

$$G_i(s) = \frac{\gamma_1 s + \gamma_2}{\alpha_3(s + a)(s^2 + 2\omega_p s + \omega_p^2)} \quad (7)$$

An investigation of the poles and zeros of Eq. (7) reveals that $\alpha \approx \gamma_0/\gamma_1$, so the transfer characteristic of the drive shaft torque can be approximately expressed as shown in Eq. (8).

$$G_i(s) \approx \frac{g_0}{s^2 + 2\omega_p s + \omega_p^2} \quad (8)$$

where

$$g_0 = \gamma_0/(\alpha_3 a)$$

By subtracting from the input motor torque $T_m$ the value obtained by multiplying the drive shaft torque $T_d$ by the differential gain $D$, Eq. (9) is obtained.

$$T_{d-c} = \frac{g_i}{s^2 + 2\omega_p s + \omega_p^2} (T_m - DS T_d) \quad (9)$$

Reorganizing Eq. (9) yields Eq. (10) expressed as:

$$T_{d-c} = \frac{g_i}{s^2 + (2\omega_p + g_i D)s + \omega_p^2} T_m \quad (10)$$

By letting Eq. (11) represent gain $D$, the attenuation coefficient of the drive shaft torque transfer characteristic becomes 1, making it possible to control drive shaft torsional vibration.

$$D = 2(1 - \zeta_p)\omega_p / g_i \quad (11)$$

In addition, by modeling the backlash characteristic of the drive shaft torque in the dead zone, it can be expressed as shown in Eq. (12) and Fig. 6. The notation $\theta_{\text{dead}}$ is the total value of the backlash from the motor to the drive shaft. By taking into account the dead zone characteristic of backlash in the vehicle model in the feedforward compensator, the compensator can calculate the feedforward torque command value for controlling drive shaft torsional vibration induced by backlash.

$$T_d = \begin{cases} K_d \left( \theta_d - \frac{\theta_{\text{dead}}}{2} \right) & \left( \theta_d \geq \frac{\theta_{\text{dead}}}{2} \right) \\ 0 & \left( -\frac{\theta_{\text{dead}}}{2} < \theta_d < \frac{\theta_{\text{dead}}}{2} \right) \\ K_d \left( \theta_d + \frac{\theta_{\text{dead}}}{2} \right) & \left( \theta_d \leq -\frac{\theta_{\text{dead}}}{2} \right) \end{cases} \quad (12)$$

3.2.2 Feedback compensator

Drive shaft torsional vibration can theoretically be suppressed by applying the feedforward compensator described in the preceding section. However, there are times when sufficient control performance cannot be
obtained in an actual vehicle due to the effects of modelling error or external force input from the road surface, among other factors, all of which are referred to here generically as disturbances. Therefore, a feedback compensator is used in parallel for the purpose of removing the effects of such disturbances.

The notation $H(s)$ used in the feedback compensator shown in Fig. 5 represents a band-pass filter. As indicated in Eq. (13) below, it serves to make the central frequency coincide with the natural vibration frequency $\omega_p$ of the controlled object.

$$H(s) = \frac{2(1-\xi^2)\omega_p s}{s^2 + 2\omega_p s + \omega_p^2}$$  (13)

In the control system shown in Fig. 5, by deriving the response of $\omega_m$ from Eq. (2) and Eq. (4) in relation to disturbance, a response without any resonance characteristic is obtained as shown in Eq. (14) below.

$$\omega_m = \frac{1}{s} \frac{\beta_3 s^3 + \beta_2 s^2 + \beta_1 s + \beta_0}{\alpha_3 (s + \alpha)(s^2 + 2\alpha \omega_p s + \omega_p^2)}$$  (14)

Figure 7 compares the frequency characteristics obtained with and without the feedback compensator.

4. In-vehicle Test Results

Figure 8 shows the vehicle response obtained in an experiment where a vehicle traveling at a speed of approximately 10 km/h was decelerated by regenerative torque and then re-accelerated by an accelerator pedal input. These driving conditions were designed to represent a situation with acceleration/deceleration inputs via the accelerator pedal while driving in a congested traffic lane under the e-Pedal mode.

In the case of the conventional control system where the backlash characteristic was not taken into account in the feedforward compensator, drive shaft torque overshoot occurred, giving rise to vehicle longitudinal vibration. With the newly developed control system in which the backlash characteristic is taken into account in the feedforward compensator, drive shaft torque overshoot did not occur, and the fluctuation amplitude of vehicle longitudinal acceleration was reduced from approximately 0.5 m/s$^2$ to approximately 0.2 m/s$^2$. These results indicate that the smooth acceleration/deceleration performance characteristic of e-Pedal was obtained.

5. Conclusion

This article has explained a newly developed method for controlling drive shaft torsional vibration induced by gear backlash. With this control method, the vehicle model in the feedforward compensator takes into account the gear backlash characteristic. This makes it possible to control the vibration due to gear backlash that occurs in situations involving a reversal of direction between regenerative torque and drive torque. As a result,
6. References


the new Nissan LEAF provides smooth acceleration/deceleration by the drive motor.
新型日産リーフのe-Pedalシステム

e-Pedal System of the New Nissan LEAF

1. はじめに

電動駆動車らしさを象徴する機能として、アクセルオフのコースト走行時にモータによる回生ブレーキを強く動作させること（以下、強コースト減速）がトレンドとなっており、日産自動車でも e-Power によって市場に供している。今回、強コースト制御に電子制御回生ブレーキシステムを融合することで、アクセルペダル操作による減速の幅をさらに広げ、車両停止も支援する「e-Pedal」を開発した。このシステムは、ドライバーのペダル踏み替え操作負荷を大幅に低減するものであり、さらに坂道での自動の停止状態

1. Introduction

A current trend in functions symbolizing the inherent nature of electric vehicles (EVs) is strong regenerative braking action by the drive motor during coasting with the foot off the accelerator pedal. Nissan provides this function, referred to here as “strong coasting deceleration,” in the e-POWER electric powertrain. Electronically controlled regenerative-friction brake coordination technology has been integrated with strong coasting deceleration control to develop the e-Pedal system that further expands the range of deceleration possible by operating the accelerator pedal alone and also assists in stopping the vehicle. The system greatly reduces the driver's operational workload involved in switching between pedals and provides peace of mind by automatically holding the stationary vehicle on slopes. Moreover, it also provides a new sensation of driving pleasure based on vehicle control by operating the accelerator pedal (Fig. 1).

This article outlines the functions, performance and benefits of e-Pedal. It also explains the results of an investigation into changes in drivers' operational behavior when using this system.
2. System Configuration

The configuration of the e-Pedal system is shown in Fig. 2. Its principal functions are located in four systems: a vehicle control module (VCM), an electrically driven intelligent brake (EDIB) system, a chassis controller and a motor/inverter system. The coordinated operation of these systems facilitates the functions of e-Pedal.

In short, the VCM calculates the target drive/braking torque based on the position of the accelerator pedal. It then sends a request for braking torque to the EDIB system, which optimally distributes the braking torque between friction braking torque and motor-based regenerative braking torque. Friction braking torque is produced by the EDIB system and regenerative braking torque is produced by the motor and inverter system via the VCM.

When stopping the vehicle, the chassis controller calculates torque for stopping and holding the vehicle according to the road grade. The EDIB system functions to hold the stationary vehicle via the friction brakes. The chassis controller also calculates torque compensation for the target drive/braking torque and illuminates the brake lamps.

3. Overview of Control Functions

The e-Pedal system is mainly composed of deceleration and stopping functions. The former consists of a deceleration function that is a key element of strong coasting deceleration, a regeneration coordination function and a regenerative-friction brake coordination function for slippery road surfaces and curves. The latter consists of a function for fully and smoothly stopping and a function for holding the stationary vehicle. These are elements for achieving comfortable and reliable stopping and holding capabilities that facilitate everyday use. The following sections explain these functions in detail.

3.1 Strong coasting deceleration function

Similar to the strong coasting deceleration function of e-POWER, this function produces larger deceleration than that of a conventional vehicle according to the accelerator pedal angle. The e-Pedal system, however, is designed to generate maximum deceleration of 2 m/s² (0.2 G). It can also cover a larger range of deceleration than e-POWER and reduces the driver’s operational workload of switching between pedals.

Figure 3 shows a distribution of deceleration occurring in the major markets of Japan, the U.S. and Europe. The results indicate that deceleration of 2 m/s² (0.2 G) covers over 90% of the frequency of driving situations requiring braking action in each market.

The high-speed region is one where strong deceleration is not frequently needed because the changes in vehicle speed are small and there is also a large deceleration effect due to wind resistance. Accordingly, the e-Pedal system is designed to suppress any jerky feeling as it does not
3.1 Deceleration in Japan

It will be noted that brake pedal operation is necessary in any driving situation where strong deceleration is needed for risk avoidance.

3.2 Regeneration coordination function

Therefore, the e-Pedal system is designed such that deceleration is compensated by friction braking when regenerative braking cannot function fully. This is accomplished by using electronically controlled regenerative-friction brake coordination technology. This electronically controlled regenerative-friction brake coordination technology is the braking system equipped on the previous Nissan LEAF model. Because regenerative-friction brake coordination is also available when the brake pedal is depressed, energy can be recovered efficiently by regeneration regardless of whether e-Pedal is turned on or off. This technology facilitates both stable e-Pedal deceleration performance and extension of the driving range.

3.3 Regenerative-friction brake coordination function for slippery road surfaces and curves

In the case of two-wheel-drive vehicles, attempting to obtain strong coasting deceleration by regenerative braking on a slippery road surface generates strong braking force only at the two drive wheels. Consequently, tire lockup tends to occur at the drive wheels, making it difficult to steer the vehicle or the vehicle is apt to start spinning. However, if regenerative braking force is weakened to avoid such states, vehicle deceleration is reduced.

In addition, if strong coasting deceleration is performed on a curve, other vehicle states must be envisioned in the event the braking force is unbalanced between the front and rear wheels. For example, front-wheel-drive vehicles may display oversteer behavior due to a tuck-in tendency or an understeer tendency due to the locking of the front wheels.

The e-Pedal system also uses electronically controlled regenerative-friction brake coordination technology to suppress such vehicle behavior. This is done by adjusting the distribution of regenerative braking torque and friction braking torque at the four wheels to match the slipping state of the drive wheels or the vehicle’s spinning state. As a result, unstable vehicle behavior is precluded while stably obtaining strong coasting deceleration, thereby enabling maximum recovery of
3.3 滑りやすい路面やケースでの回生摩擦制動機能

滑りやすい路面において、回生ブレーキにより实现しようとすると、2輪駆動車の場合は駆動輪の2輪のみ大きな制動力が発生するため、制動輪が容易にタイヤロック傾向となり制動が効かない、あるいは車両がスピノンに陥るといった状態になりやすい。しかしこれを避けるために回生ブレーキトルクを弱めると、車両に発生する減速度が小さになってしまう。

またケースにおいて強コースト減速を行う場合、前後の制動バランスが偏っている場合、例えば前方輪駆動車の場合でアクセルペダルによるオーバーステア挙動や、前輪ロック傾向によるアングスタテステーション傾向を想定しなければならない。

e-Pedalでは、そのような車両挙動の抑制のためにも電子制御回生ブレーキ技術を活用している。すなわち、駆動輪のスリップ状態や車両の旋回状態に応じて回生ブレーキと2輪への摩擦ブレーキの配分を調整し、強コースト減速を安定的で実現したまで不安定な車両挙動を未然に防ぎ、回生によるエネルギー回収も最大限に行うことができる。

一方、氷結路面などの極めて滑りやすい路面では、摩擦ブレーキにより4輪の制動力分配を最適化してもタイヤがロック傾向になることがある。これは実現しようとしているコースト減速度が、路面μに対して大きいすぎることが原因である。アクセルペダルを少し踏み込みコースト減速度を弱めることで回避できるが、この操作には慣れが必要である。そこでe-Pedalでは、4輪への摩擦ブレーキのみでの制動に切り替えてもなおタイヤロック傾向が見られるときは、システムが要求するコースト減速度を自動的に小さく補正している。この際、タイヤロック傾向が確実に収まるコースト減速度まで補正を行うことで、タイヤの摩擦力に余裕を持たせることができるため、ドライバのステアリング操作とブレーキペダル踏み込み操作において余地を残すことができ、滑りやすい路面においてもドライバ自身でのコントロール性を維持できる。

3.4 坂道助勾配補正機能

上り坂に合わせてアクセルペダルを踏み増すこと、下り坂で車速が上がり過ぎないようにブレーキペダルに踏み替えることなどのペダルの調整操作を少なくするために、道路

energy through regeneration.

On icy and other extremely slippery road surfaces, there are times when the tires may tend to lock up even though the braking force distribution to the four wheels is optimized by the friction braking system. This is caused by the fact that the desired coasting deceleration is too large for the road surface μ. It can be avoided by depressing the accelerator pedal slightly to lessen coasting deceleration, but this operation requires experience on the driver’s part. Accordingly, e-Pedal automatically corrects and reduces the coasting deceleration requested by the system if a tire lockup tendency is apparent even after switching solely to braking by the friction brakes at all four wheels. At this time, coasting deceleration is corrected until the tire locking tendency is reliably controlled. Because this gives the tires some friction force margin, it leaves leeway for the driver’s steering action and further depression of the brake pedal. Therefore, it maintains drivers’ capability to control the vehicle themselves on slippery road surfaces.

3.4.1 Function for complete, smooth stopping

When the driver releases the accelerator pedal while driving, accurate control of the driving force of the drive motor functions to decelerate the vehicle to a speed of 0 km/h, bringing it to a complete stop. In order for the drive motor to completely stop the vehicle on a slope, precise motor control is required for generating drive torque matching the road grade at exactly the same time the vehicle reaches a speed of 0 km/h.
Motor torque control is performed to reduce any vehicle jerking just before the vehicle is brought to a stop. This makes it possible to stop the vehicle smoothly, like an experienced driver does, without needing to adjust the accelerator pedal.

It will be noted that the road grade range in which the vehicle can be completely stopped just by releasing the accelerator pedal is from an uphill grade of approximately 30% to a downhill grade of approximately 10%. This range was defined to avoid giving the vehicle occupants any unnatural feeling due to a physical perception of excessively strong braking between braking by the e-Pedal system and acceleration due to gravity.

### 3.5.2 Function for holding stationary vehicle

After the vehicle stops completely, a transition occurs from a stopped state due to drive motor torque to a state of holding the stationary vehicle by the friction brake system. The necessary friction braking force is calculated based on the estimated road grade mentioned above. The stationary vehicle can be held on both uphill and downhill grades of up to approximately 30%.

The e-Pedal system also incorporates a function for increasing the friction braking force if vehicle movement such as slipping backward is detected while it is being held by the e-Pedal system. This ensures more reliable holding of the stationary vehicle. It also mitigates any change in vehicle behavior before the driver applies the brake pedal in the event that the vehicle moves on a slope or in some other place.

### 4. System Benefits and Investigation of Change in Driving Behavior

#### 4.1 Benefit of reducing driver’s workload

Figure 4 shows the number of brake pedal applications with/without the e-Pedal system. Cases A to D are the results obtained during urban driving in the U.S. and cases E to H are the results for urban driving in Japan. The course, distance driven, time and other measurement...
e-Pedal System of the New Nissan LEAF

conditions differed in each case. However, it is seen that the number of brake pedal applications was substantially reduced with the e-Pedal system in all the driving tests. These results indicate that the e-Pedal system contributes to reducing the driver’s workload of switching between pedals. In addition, the reduction rate of around 90% agrees reasonably well with the envisioned effect based on the deceleration distribution shown earlier in Fig. 3 for three selected markets.

Figure 5 shows the results of an analysis of the factors involved in the brake pedal applications in Fig. 4. The greater majority of the applications were for deceleration. However, it is inferred that the amount of reduction in brake pedal applications is influenced by various factors such as the driving environment, individual driving styles and the amount of experience with the system. Therefore, it is difficult to discuss the variation seen in the reduction effect in each driving test. Brake pedal application for the purpose of deceleration means that there were driving situations where deceleration exceeding that set for e-Pedal was necessary. Even in those situations, the driver was able to depress the brake pedal.

The single application of the brake pedal measured in all driving tests at start-off is attributed to the test vehicle specifications themselves. Such instances should be excluded from any examination of the effectiveness of the e-Pedal system. In contrast, brake pedal application while the vehicle was stopped is only seen in limited cases. This is attributed to the effect of the system in reliably holding the stationary vehicle by the friction brake system. Therefore, it contributed to reducing the driver’s operational workload.

Figure 6 compares drivers’ behavior with and without the system when driving on a winding downhill road. In this evaluation, the preceding vehicle was equipped with the e-Pedal system and the following vehicle was not. This method was used to avoid any large difference in the average driving speed. The vehicles were driven under the assumption of ordinary speed limits.

The results show a large difference in brake pedal

4. システムの効果と運転行動の変化の検証

4.1 運転負荷の軽減効果

図4に、e-Pedal機能の有無におけるブレーキペダルの操作回数を記載した。シーエンスA～Dは北米、シーエンスE～Hは日本で市街地を走行した結果である。各シーエンスによってコースや走行距離、時間など計測条件は個々に異なるが、全ての試行においてブレーキペダルの操作回数が大幅に減少しており、本システムがペダル踏み替え操作負荷の低減に貢献していることがわかる。また低減率が90%程度であることは、先の各国の減速度分布（図3）に基づく効果想定と概ね一致している。

図5は図4におけるブレーキペダル操作の要因を分析したものである。ブレーキペダル操作の大部分が減速操作のためのものであった。ただし、ブレーキペダル操作の低減は市場環境や運転スタイル、システムへの慣れ具合など様々な要因により左右されると推察され、試行行ごとの低減効果のばらつきに対する考察は難しい。減速のための操作があったということは、e-Pedalの減速度設定を超える走行シーエンスがあったことを意味するが、そのような場面でもドライバがブレーキペダルを操作できているということである。

全ての試行回において、起動時に1度のブレーキペダル操作が計測されているのは、評価車両自体の仕様によるものであり、e-Pedalの効果検討から除外して考えるべきである。その一方、停止中のブレーキペダル操作が限られた回数しか見られないことは、摩擦ブレーキにて確実な停止
保持を行う本システムの効果を示しており、ドライバーの運転負荷軽減に貢献するものである。

次に、下り坂ワインディング路において、e-Pedal機能の有無による走行比較を行った（図6）。平均速度に大きな差がないように前走車がシステム有り車で、システム無し車がそれに従従する方法で、一般的な制限車速を想定して走行した。

その結果、まずブレーキペダルの操作に大きな違いが見られた。システム無し車が速度調整のためにたびたびブレーキペダルを操作している一方で、システム有り車ではブレーキペダルの操作は全くなく、アクセルペダルの操作のみで評価区間を下りきっている。意図せず車速が上がり、あるいはカーブ直前での車速調整が必要となる度に、アクセルペダルからブレーキペダルに踏み替えざるを得ない煩わしさや操作負荷が、e-Pedalによって大幅に低減したのである。

4.2 車速変化や前後加速度の平滑化効果

下り坂ワインディング走行を行った図6をさらに確認する。システム有り車のアクセルペダル操作を見ると、全盤まで戻されることは数回程度であり、ドライバーが常にアクセルペダルを操作し車速を調整している様子がわかる。その結果、システム有り車はシステム無し車に比べ車速の変動幅が小さく、前後加速度も滑らかに推移していることがわかる。

図7は図6の一部を拡大したものである。システム無し車において、ブレーキペダル操作と車速変化のオーバーシュートに関連性があることがわかる。点線矢印で示したapplication. The driver of the vehicle without the system frequently applied the brakes to adjust the vehicle speed. In contrast, the driver of the vehicle with the e-Pedal system never depressed the brake pedal at all and drove down the evaluation course by operating only the accelerator pedal. Whenever the vehicle speed rose unintentionally or it was necessary to adjust the speed just before a curve, the e-Pedal system markedly reduced the troublesome operational workload of having to switch from the accelerator pedal to the brake pedal.

4.2 Benefit of smoothing vehicle speed changes and longitudinal acceleration

Figure 6 shows the results of a further confirmation of the effectiveness of the system when driving on a winding downhill road. An examination of the operation of the accelerator pedal of the vehicle with the e-Pedal system shows that there were only a few instances when the pedal was returned to a fully released position. This indicates that the driver was constantly operating the accelerator pedal to adjust the vehicle speed. As a result, the range of change in the vehicle speed was smaller for the vehicle with the system than for the one without it. This indicates that lateral acceleration also changed smoothly for the vehicle with the system. Figure 7 presents an enlarged view of some of the data in Fig. 6.

For the vehicle without the system, a relationship is seen between brake pedal application and overshoot of the change in vehicle speed. As indicated by the dashed-line arrows, the brake pedal was depressed right after the vehicle speed rose to a higher level and the pedal was released after the vehicle speed became too low. This driving pattern is frequently seen.

![Fig. 6 Driver's behavior in downhill driving](image6)

![Fig. 7 Enlarged detail of Fig. 6](image7)
e-Pedal System of the New Nissan LEAF

通し、車速が高めになった直後にプレーキペダルが踏み込まれ、車速が低くなりすぎてからプレーキペダルが離される運転動作が多く見られる。

また、点検線の矢印で示したように、システム有り車において、アクセルペダル回帰による減速、踏み込みによる再加速が、システム無し車でのブレーキペダル操作より早いタイミングで行われていることがわかる。このような運転操作行動の変化が、不要な車速の変動を低減し、前後加速度の滑らかな推移として現れる。

図8はアクセルペダル操作と前後加速度の関係を示しており、アクセルペダル操作に対して加減速が連続的につながっていることがわかる。この特性は滑らかな車速コントロールを、アクセルペダル操作による前後荷重バランスの微調整を容易にし、ハンドリング性能の向上にもつながる。

さらに、この特性は氷結路面などの細かいタイヤの駆動制动力コントロールが必要な場面においても有効である。図9はシステム有り車で雪道において減速および微速進行を行った際の実験データである。アクセルペダルの調整によって滑らかに減速度を高め、車速15km/h近辺でアクセルペダルを完全に戻っている。アクセルペダル操作で大きい減速までカバーしていること、および前述の四輪駆動車の回生ブレーキ機能によるタイヤスリップ時も安定した減速度を維持できることから、雪道においてもアクセルペダル回帰で必要な減速度が得られやすく、アクセルペダルの調整により容易に車速のコントロールがでえる。

さらにその後、停止直前にアクセルペダルをわずかに踏み込んで。タイムチャート上の車速は車輪速度の算出ロジックの都合で0km/hを示しているが、実際は1km/h前後で微速進行しているシーンである。アクセルペダル操作で減速から加速側に連続的に駆動力をコントロールできることや、アクセルペダル操作に対して駆動力が正確に連動することから、雪道においても思うままに駆動力を車速のコントロールが可能となり、タイヤスリップや前後加速度の急な変化もなく、滑らかな運転が可能となる。

In addition, as indicated by the dot-dashed-line arrows, deceleration by returning the accelerator pedal and re-acceleration by depressing it occurred at an earlier timing for the vehicle with the system than for the one without it. This difference in driving behavior appeared because unnecessary changes in vehicle speed were reduced by the e-Pedal system to support smooth longitudinal acceleration.

Figure 8 shows the relationship between accelerator pedal operation and longitudinal acceleration/deceleration with and without the system. The results reveal that acceleration/deceleration was continuously linked to the operation of the accelerator pedal. This characteristic facilitates smooth control of the vehicle speed and makes it easy to finely adjust the load balance between the front/rear wheels by operating the accelerator pedal, thereby leading to improved handling performance.

Moreover, this characteristic is effective in situations where fine control of the drive/braking force of the tires is necessary such as on icy road surfaces. Figure 9 presents test data for deceleration and crawling with a system-equipped vehicle. Adjustment of the accelerator pedal smoothly increased deceleration, and the accelerator pedal was fully returned at around a vehicle speed of 15 km/h. Operation of the accelerator pedal is effective even for large deceleration, and stable deceleration can be maintained by the regenerative-friction brake coordination function explained earlier even when the tires are slipping. These capabilities make it easy to obtain the necessary deceleration by returning the accelerator pedal even on snow-covered roads. This enables easy vehicle speed control by simply adjusting the position of the accelerator pedal.

Subsequently, the driver lightly depressed the accelerator pedal just before the vehicle stopped. Because of the nature of the calculation logic used for determining the wheel speed, the time graph shows a speed of 0 km/h,
but the vehicle was actually creeping at a speed of around 1 km/h in this situation. Operation of the accelerator pedal enables continuous driving force control from deceleration to acceleration, and driving force is accurately linked to the operation of the accelerator pedal. These capabilities make it possible to control both the driving force and vehicle speed as the driver wishes even on snow-covered roads. This facilitates smooth driving without any tire slipping or sudden changes in longitudinal acceleration.

These driving characteristics relieve the driver’s stress and allow relaxed driving even on icy road surfaces where careful attention must be paid to the operation of the accelerator pedal and brake pedal.

4.3 Changes in driving behavior

Unlike a conventional automatic transmission (AT) vehicle, the operational style suitable for smooth driving with the e-Pedal system is for the driver to constantly adjust the accelerator pedal appropriately without completely releasing the pedal. Accordingly, it is assumed that drivers’ degree of experience with this system will appear in their manner of operating the accelerator pedal.

Figure 10 shows the amount of accelerator pedal operation and distance to a stopping target when the vehicle was decelerated toward the target and stopped by just operating the accelerator pedal. A comparison is made between driving behavior before and after the subjects gained experience with the operation of the e-Pedal system. Subjects without any experience with the system completely released the accelerator pedal even for slight deceleration and then subsequently repeatedly depressed the pedal. As a result, operation of the accelerator pedal involved more work, and the rate of deceleration was not constant. In contrast, after experiencing the operation of the system during driving for about one hour, they suitably adjusted the accelerator pedal without completely releasing it and also brought the vehicle to a stop at a constant rate of deceleration.

5. Conclusion

The e-Pedal system adopted on the new Nissan LEAF combines electronically controlled regenerative-friction brake coordination technology with the strong coasting deceleration function of e-POWER. This expands the range of deceleration possible with the accelerator pedal and also supports the capability to stop and hold the vehicle. Consequently, vehicle speed control by means of the accelerator pedal alone is possible in nearly all everyday driving situations. As a result, the frequency of switching between pedals is markedly reduced to lighten the driver’s operational workload.

Driving with the e-Pedal system requires suitable adjustment of the accelerator pedal at all times, which tends to differ from pedal operation in conventional AT-equipped vehicles. However, it is easy to become familiar with the method of driving with e-Pedal. Once drivers are familiar with the system, smooth vehicle...
motions and other benefits are reliably obtained.

6. References

1. Introduction

Nissan began focusing on the potential of lithium-ion batteries for automotive use in 1992 ahead of other competitors and has continuously pursued R&D efforts for electric vehicles (EVs), hybrid electric vehicles (HEVs) and fuel cell electric vehicles (FCEVs), including repeated market introductions of these vehicles. By making effective use of the know-how gained in this process, Nissan has developed a complete and coherent suite of electric vehicle technologies, ranging from the battery cell level to the vehicle level. In 2010, the Nissan LEAF mounted with a lithium-ion battery was launched as the world’s first mass-produced EV.1-3)

The knowledge gained with the first-generation Nissan LEAF, including information on driving styles unique to EVs, has been reflected in all the components and in the design of every battery part. Consistent efforts

Key words: Automotive General, electric vehicle (EV), new model, lithium-ion battery, battery pack design, lithium-ion cell, laminated cell

1. は じ め に

日産自動車は1992年から競合他社に先駆け、リチウムイオンバッテリーの自動車用途への可能性に着目し、電気自動車（EV）、ハイブリッド車（HEV）、燃料電池車（FCEV）に向けた研究開発、市場投入を重ねてきた。そこで得られたノウハウを活用しつつ、セルから電流まで一貫したトータル的な電動車両の技術開発を行い、2010年にリチウムイオンバッテリーを使用した世界初の量産型電気自動車（EV）の日産リーフを発売した1-3)。

初代日産リーフから得られた知見（電動車両用の使われ方など）を各コンポーネント、そしてパッテリの各部品設計へ反映し、基盤技術、生産技術開発を地道に積み重ね、車両適合を継続して行った。この結果、2代を越えるマイナーチェンジを実施し、航続距離などの車両性能も進化させてきた。そして、今回2017年10月に大容量リチウムイオンバッテリーを搭載し、フルモデルチェンジとなる新型日産リーフを発売した（図1）。

航続距離、動力性能（出力力特性）などの電動車両性能は主にパッテリ性能が基盤にあり、性能に大きく依存する。特に、航続距離は所定バッテリーサイズでのエネルギーよりの増加、すなわち、体積あたりのエネルギー密度の向上が重要となる。今回、新開発の大容量40 kWhバッテリは、初期型24kWhに対し、エネルギー密度を約67%と向上させ
41
NISSAN TECHNICAL REVIEW No. 82 (2018–3)

High-capacity Lithium-ion Battery for the New Nissan LEAF

have been made to develop fundamental technologies and production engineering techniques and to adapt them continuously to vehicles over the years. As a result, the driving range and other performance attributes of the Nissan LEAF have continually evolved through the execution of two minor model changes. A full model change was then carried out and the new generation of the Nissan LEAF fitted with a high-capacity lithium-ion battery was put on the market in October 2017 (Fig. 1).

The performance of an EV, including its driving range, power performance (input/output characteristics) and other attributes, is largely dependent on the fundamental performance of the battery. For the driving range in particular, it is important to increase the amount of energy stored in a given battery size, i.e., to improve the energy density per unit volume. The newly developed high-capacity 40 kWh battery has approximately 67% more energy density than the 24 kWh battery used on the first-generation model. This improvement made it possible to equip the new Nissan LEAF with a higher capacity battery without changing the battery size, thereby achieving a driving range of 400 km under Japan's JC08 emission test mode. The driving range is double that of the first-generation model with a 24 kWh battery and more than 40% greater than that of the minor-change model with a 30 kWh battery (Fig. 2).

This article describes the development of this high-capacity lithium-ion battery used on the new Nissan LEAF.4)

2. Development Overview of High-capacity Battery

The energy density per unit volume of the newly developed high-capacity 40 kWh battery was improved by approximately 67% through two principal measures, while achieving a balance between performance and reliability. One measure was to adopt electrode materials with high energy density for the cells. The other was to improve the volumetric efficiency of the modules and pack. The increase in weight due to the higher capacity was held to around 10% by optimizing the battery structural members. In addition, input/output characteristics and durability were also improved by enhancing cell performance.

2.1 Battery layout design

The battery layout design must ensure roomy

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interior space, a low center of gravity for vehicle operational safety and protection of the battery against external force inputs. From these perspectives, the battery must be mounted under the cabin floor in a flat state within a limited space (Fig. 1). The component layout of the new 40 kWh battery fitted on the new Nissan LEAF is shown in Fig. 3, and a battery circuit diagram is shown in Fig. 4.

Like the previous batteries, the modules of the new battery consist of a stack of laminated cells and are laid out according to the floor geometry. In addition to the modules, the battery pack includes a battery management system (BMS) that monitors and controls the battery internal state, a junction box (JB) that turns On/Off the high voltage, and a service disconnect switch (SD/SW) to ensure safety when maintenance work is done. In connection with the higher capacity and higher output of this new battery, the performance of auxiliary parts such as the fuses and current sensor was reviewed and their installation positions were optimized. A heater was also adopted for keeping the battery warm on vehicles shipped to very cold regions.

The new battery comprises an integrated package of all the parts and functions needed by an EV battery.

### 2.2 Battery specifications

The major specifications of the new 40 kWh battery used on the new Nissan LEAF are listed in Table 1 in comparison with those of the first-generation 24 kWh battery.

#### 2.2.1 Adoption of high-energy-density electrode materials for a new cell

A new cell was developed to obtain higher capacity and lower resistance for use in the new 40 kWh battery. The cathode material was changed from the previously used lithium manganese oxide (LiMn₂O₄) with a spinel crystal structure to a three-element mixed material consisting of nickel, manganese and cobalt (NMC) with a new layered structure. This NMC material stores a high density of lithium ions in its crystal structure, giving it a...
High-capacity Lithium-ion Battery for the New Nissan LEAF

capacity ratio 0.6 times greater than that of the previous manganese system (Fig. 5).

However, because the high-energy-density NMC material has a layered structure, there was concern that its crystal structure might be weaker and its reliability lower in an overcharged condition compared with the previous manganese material. Accordingly, in order to improve robustness and reliability, the material composition ratio of NMC as well as the constituent materials and parts, as typified by the separator structure, were optimized, and the cell design was executed so as to achieve a total balance of performance and reliability. These measures improved the high energy density of the battery without sacrificing cell reliability.

In addition, cell internal resistance was reduced by 50% from that of the previous cells by lowering the resistances of the anode/cathode materials, electrode physical properties and electrolyte and also by optimizing the layered structure of the cells (Fig. 6).

2.2.2 Improvement of volumetric efficiency of modules and pack

The new 40 kWh battery has an improved module structure compared with that of the first-generation 24 kWh battery. With the previous laminated cell, four cells were stacked to form one module. In contrast, for the newly developed module, eight cells are stacked to form one module, and two modules are integrated. The module structure was optimized so that suitable pressure would be applied to the cells in consideration of the increased module weight resulting from integration and the increased thickness due to the higher cell capacity. As a result, the same external pack dimensions were achieved as those of the previous battery pack, and the cell packing density (capacity increase per unit volume) inside the pack was improved (Fig. 7).

The results of a simulation of pack heat generation during charging and discharging showed that a large capacity of 40 kWh was attainable without adding any cooling structure, the same as for the previous battery pack.

The maximum output of the motor used on the new Nissan LEAF was increased to 110 kW compared with 80
だけでなく、測定精度の高い回路もセンサに追加し、車両として表示される航続可能距離の算出精度を向上させた。

3. バッテリ特性

上記で説明したセル、モジュール、バック開発を行うことにより、新型日産リーフに搭載した新開発40kWhバッテリは、初期型24kWhバッテリからサイズを変更することなく、バッテリのエネルギー密度を向上させ、航続可能距離400km（JC08）を達成している。また、セルの低抵抗化により、バッテリの入出力特性も向上している。

まず出力特性に関しては、新開発40kWhバッテリはほぼ全SOC（State of charge）領域で、新型日産リーフのモーター出力110kWを対応可能としている（図8）。同様に新開発40kWhバッテリは、入力特性も向上している。急速充電（50kW）において、40分後の充電容量を比較した場合、初期型24kWhに対し、常温では容量比で約60％、そして低温では約2倍も向上し、実用性を向上させた（図9）。

一方、耐久性に関しては、下記のセル開発を行うことにより、大幅な性能向上を実現した。
①正負極材料、電解液の構成部材の性能向上
②正負電極構成と電極物性の最適化
③トータルバランスをとったセル設計の最適化

3. Battery Characteristics

The development of the cell, module and pack as described above improved the energy density of the new 40 kWh battery used on the new Nissan LEAF without changing the battery size from that of the first-generation 24 kWh battery, thereby attaining a driving range of 400 km under the JC08 emission test mode. In addition, the reduction of cell internal resistance also improved the input/output characteristics of the battery.

First, with regard to output characteristics, the new 40 kWh battery enables the motor used on the new Nissan LEAF to generate its maximum power of 110 kW in nearly all state of charge (SOC) regions (Fig. 8). Likewise the new 40 kWh battery also features improved input characteristics. A comparison of the battery capacity after 40 minutes of rapid charging at 50 kW is shown in Fig. 9. The charge capacity of the new 40 kWh battery was approximately 60% higher than that of the first-generation 24 kWh battery at normal temperature and nearly double that of the latter at low temperature. This improvement has enhanced the practical performance of the new Nissan LEAF (Fig. 9).

Battery durability has also been greatly improved as a result of taking the following measures during the cell development process.
⑴ Improvement of the performance of anode/cathode materials and constituent materials of the electrolyte
⑵ Optimization of the anode/cathode composition and electrode properties
⑶ Optimization of the cell design for a total balance of performance and reliability
⑷ Optimization of cell production process requirements and quality control

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**Fig. 10**  Estimated of battery durability

**Fig. 9**  Charge characteristics of battery

kW for the first-generation model. Because the maximum current flowing in the battery was increased, the functionality of the current sensor for measuring the current value was improved. Besides expanding the measurable current range over that of the previous sensor, a circuit for obtaining high measurement accuracy was also incorporated in the sensor. This has improved the calculation accuracy of the vehicle’s allowable driving range.
Capacity retention rates were estimated for the first-generation 24 kWh battery after five years and the new 40 kWh battery after eight years. The results in Fig. 10 show that an estimated increase of 10% in capacity retention can be expected for the new battery. As a result, the capacity warranty period of the new 40 kWh battery has been extended to eight years or 160,000 km from the date of new vehicle registration, compared with five years or 100,000 km for the first-generation 24 kWh battery. (The warranty covers parts for capacity up to nine bars on the battery capacity gauge in the event that the gauge falls below nine bars.)

4. Battery Reliability Design

Targets for battery reliability are set based on the market environment and the ways in which customers drive their vehicles. Battery reliability is assured by equipping vehicles with batteries showing test results that satisfy the reliability targets (Fig. 11). This is achieved by assuring the durability of the battery pack as noted in items (1) and (2) below and pack protection as noted in item (3).

(1) Optimal allocation of reliability targets to each level making up the system (from the highest level: vehicle → pack → module → cell)
(2) Conversion of stress required by the vehicle environment to reliability targets
(3) Commitment on the safe side through control and failsafe measures in the optimal range of each type of control

Moreover, in order to assure safety in the event the pack is rendered out of control, safety requirements are also built in as prescribed by the laws, regulations and standards of the countries where the vehicle is used. The steadfast efforts made to build in these safety requirements contribute to achieving a record of zero serious problems.

5. Conclusion

This article has described the important cell design, module/pack design, reliability design and battery...
5. ま と め

今回、大容量40kWhのリチウムイオンバッテリ開発において重要なセル設計、モジュール/パック設計、信頼性設計、およびバッテリ特性の紹介を行った。航続距離の延長、入出力特性の向上、そして耐久性能の向上など、新型日産リーフの商品性向上に大きく貢献している。

今後はEVの本格普及、魅力的な車両性能の提供に向け、下記を軸とするバッテリの高エネルギー密度化を進め、低コストで、性能と信頼性のバランスをとれたバッテリ開発を継続していく（図12）。
①更なる正極・負極高容量材料の適用、高極物性と構成物の最適化によるセルのエネルギ密度向上
②モジュール/パック構造の抜本的な見直しによるパッケージのセル充填率向上

6. 謝 辞

最後に、今回の大容量40kWhリチウムイオンバッテリの開発、製品化にあたり、サプライヤを含む社内外関係各部署の方々に、多大のご尽力を頂きました。
本書面を借りて厚く御礼の意を表します。

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characteristics that were developed for the new high-capacity 40 kWh lithium-ion battery. The resultant extended driving range, improved input/output characteristics and enhanced durability, among other attributes, have contributed significantly to improving the product appeal of the new Nissan LEAF.

We intend to continue our efforts to achieve higher energy density through the measures noted below and further develop low-cost batteries with a good balance of performance and reliability (Fig. 12). Such batteries will help to promote the full-fledged penetration of EVs in the coming years and to provide attractive vehicle performance.
(1) To enhance cell energy density by applying anode/cathode materials with even higher capacity and by optimizing the properties and material composition of the electrodes.
(2) To improve the cell packing density in the battery pack by thoroughly reviewing the module/pack structures.

6. Acknowledgments

The authors would like to take this opportunity to thank everyone inside and outside the company, including the suppliers, for their invaluable cooperation with the development and commercialization of the new large-capacity 40 kWh lithium-ion battery.

7. References

High-capacity Lithium-ion Battery for the New Nissan LEAF
1. Introduction

Expanding the charging infrastructure is absolutely necessary for supporting the penetration of electric vehicles (EVs). Nissan has been promoting the implementation of charging stations in conjunction with the market release of the company’s EVs. Because EV batteries can be charged from the home power supply, fuel replenishment at service stations like that for internal combustion engine (ICE) vehicles is not necessary. EVs also have an advantage with respect to operating costs. However, for traveling long distances or in situations where it is desired to charge the battery quickly, quick charging for extending the driving range in a short period of time is necessary. Toward that end, charging standards have been studied in recent years for increasing the current and voltage of quick chargers.

This article describes the technological and
The Latest Status and the Outlook of Quick Charging

2. Quick Charging Systems and Penetration Status

Quick charging standards can be classified into three main types: the CHAdeMO standard originated in Japan, the CCS standard originated in Europe and the GB/T standard originated in China. The CHAdeMO standard was issued by the CHAdeMO Association established in 2010. This association has been standardizing for quick charger specifications with high safety and compatibility. At present, over 7,000 quick chargers complying with the CHAdeMO standard have been installed in Japan and more than 16,000 have been installed worldwide. These numbers are continuing to increase (Fig. 1). A charger certification system has also been established, enabling third-party institutions to conduct certification tests.

3. Technological Trends for Quick Chargers

3.1 V2X

V2X refers to a concept that allows the provision of electric energy from EVs to other electrical systems, such as Vehicle to Home (V2H) and Vehicle to Grid (V2G) applications. V2H systems for general home use began to be commercialized in Japan in 2012, and several thousand units have been installed for general home use. These units have economic benefits for users by shifting electric power consumption away from the peak period. They can also be utilized as an emergency power source during power outages. In addition, use as a virtual power plant (VPP) is also expected and verification trials have been started in various countries in addition to Japan. In this case, the Internet of Things (IoT) technology is used to link together energy sources dispersed geographically to form a single power plant that functions as a VPP.

3.2 Dynamic control

Dynamic control refers to a function for dynamically varying the maximum output of a quick charger during charging. On holidays and other occasions, waiting lines form for charging EV batteries with quick chargers that are used by many people at service areas/parking areas along expressways, among other places. This function enables the output of a quick charger equipped with multiple charging connectors to be suitably distributed according to the charge acceptance capacity of the EV.
塩基をエネルギーの源を、IoT（Internet of Things）を活用して統合し一つの発電所のように機能させる、いわゆるVirtual Power Plant（VPP）としても期待されており、日本のみならず各国で実証実験が始まっている。

3.2 ダイナミックコントロール

ダイナミックコントロールは、充電中に急速充電器の最大出力を動的に変更できる機能である。高速道路のサービスエリアなど利用者が多い急速充電器では、充電待ちが発生することがある。そこで1台の急速充電器で複数の充電コネクタを備えることで、1台のEVを充電するとき

に最大出力で充電し、複数台のEVを充電するときにはEVの充電量に応じて適切な出力配分を行うことで、充電待ちを低減する（図2参照）。

3.3 ハイクレントコントロール

ハイクレントコントロールは、充電時間の短縮やEVに搭載されるバッテリの容量増加に対応するため、充電電流を最大400Aにまで拡張することを可能とする。充電電流の増加によるコネクタ付ケーブルでの発熱増を抑えるためにはケーブルの導体径を太くする必要があるが、ケーブルの重量の増加や、取り回しが悪くなるといった影響があり、ユーザーの利便性を損なうことになる。それを回避するため、コネクタ付ケーブル内の導体を冷やすことで、従来と導体径を変えずに大電流を流す仕様を规格化した。また、コネクタ付ケーブルに温度監視機能を設け、適度な温度上昇が起こらない範囲で充電することで、一時的に大電流を流す短時間定格電流を用いた運用も可能とした（図3参照）。一方、コネクタ付ケーブルに冷却用ホースを搭載することについては、レイアウト上の制限や、冷却効率の改善、コネクタの落下やケーブルの踏みつけなどに対する耐久性をどのように確保するかという課題があり、今後の技術向上が求められる。

3.4 マルチアウトレット

複数のコネクタを持つマルチアウトレットは、前述のダイナミックコントロールと組み合わせた使い方や、異なる充電方式（例えば、CHAdeMOとCSSなど）のコネクタを持つことにより、充電できる対応車種を増やすことが可能となる。

batteries to be charged. A single EV can be charged using the maximum output, and multiple EVs can be charged by distributing the output accordingly, thereby reducing the waiting time for charging (Fig. 2).

3.3 High current control

High current control makes it possible to raise the charging current to a maximum of 400 A so as to reduce the charging time or to cope with the increased capacity of batteries installed on EVs. Because raising the charging current causes the connectors and cables to generate more heat, it is necessary to increase the diameter of the cable conductor for suppressing heat generation. This has various undesirable effects such as increasing the cable weight and worsening handling ease, which impair user convenience. To avoid such effects, a specification has been standardized for cooling the conductor inside cables, thereby enabling the flow of high current without changing the diameter from the conventional conductor.

In addition, a temperature monitoring function has been applied to connectors and cables so that charging is performed within a range where the temperature does not rise excessively. This has also made it possible to operate quick chargers using a short-term rated current that passes a high current temporarily (Fig. 3). On the other hand, the provision of a cooling hose in connectors and cables is limited by the layout. There are also other issues such as how to improve cooling efficiency and how to ensure connector durability against dropping and cable durability if stepped on. Technologies must be improved to deal with such issues.

3.4 Multi-outlets

The use of a multi-outlet with multiple connectors can increase the types of vehicle models that can be charged by combining it with dynamic control described above or by using a charger equipped with connectors for different charging systems like CHAdeMO and CSS.

In addition, the use of higher charging voltage is being considered as a new specification to be included in the next standard revision. It is possible that the existing charging voltage limit of 500 V may be extended to 1000 V. Charging infrastructure is being prepared in connection with the increase in the onboard battery capacity. However, voltage above 750 V is classified as high voltage in Japan, so efforts are needed to address installation and operational

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![図-2 ダイナミックコントロールの適用例](image)

**図-2 Example of the use of dynamic control**

![図-3 コネクタ付ケーブルの冷却と温調監視の基本構成](image)

**図-3 Basic configuration for cooling and monitoring the temperature of cables and connectors**
The Latest Status and the Outlook of Quick Charging

4. Creation of International Quick Charging Standards

Work is under way globally to establish international standards to enable charging under the same standards worldwide, not only in Japan (Table 1). The CHAdeMO standard has also been adopted in the International Electrochemical Commission (IEC) standards. Charging system specifications are specified in IEC 61851-23 and connector specifications in IEC 62196-3. In addition, discussions are under way to incorporate a cable standard in the IEC 62893-4 standard.

The IEC 61851-23 charger standard document lists common requirements for the DC chargers used for EVs. In addition, the CHAdeMO system is specified in Annex AA, the GB/T system in Annex BB and the CCS system in Annex CC. Edition 1 was issued in 2014. Revision discussions are now under way for the creation of Ed. 2. Discussions on increasing the current and voltage of chargers are proceeding as requirements to be added to Ed. 1. Preparations are being made to expand the charging power of each system. Studies are also being carried out for adding a multi-outlet specification for chargers equipped with multiple connectors and a V2X specification for enabling EVs to provide electric power to home electric wiring and outlets, in addition to charging.

5. Expansion of CHAdeMO Technology beyond Passenger Vehicles

The trend toward electrification in recent years has not been limited to passenger vehicles, but also includes large vehicles like buses and trucks as well as motorcycles. In addition, charging systems are also being diversified to include pantograph and wireless charging (Fig. 4). In order to expand the benefits of standardization to cover a wider range of electrified vehicles, the CHAdeMO Association issues, including revising the related laws, regulations and standards.

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is currently preparing a specification for accommodating various types of charging systems, while inheriting the core technologies of CHAdeMO.

6. Conclusion

Nissan has vigorously promoted efforts to standardize quick chargers and to expand their use with the aim of supporting the penetration of EVs. Further evolution of quick chargers in the future is also necessary in view of the expected extension of the driving range of EVs. At the same time, increasing the charger output to unprecedented levels will involve the use of high current and high voltage. In this regard, it will be increasingly important to resolve various installation and operational issues and to establish the related laws, regulations and standards. As Nissan targets to be an EV leader, more will be expected of the company not only regarding vehicles, but also for infrastructure implementation and standardization activities in order to promote the further expansion of quick chargers.

7. References

1. Introduction

Activities to reduce the environmental impact of vehicle are imperative if vehicles are to continue to exist as viable elements of the sustainable society. Toward that end, vehicle manufacturers are vigorously advancing a shift toward powertrain electrification. Nissan has been a leading company in promoting electrification beginning with the Nissan LEAF and is continuing to work hard on electrification as a top-priority strategy. However, at present there are various issues including infrastructure aspects that remain to be overcome in order to promote the global diffusion of electrified vehicles such as electric vehicles, fuel cell vehicles and other types without an internal combustion engine (ICE). Given this reality, it is presumed that ICE vehicles will continue to represent the mainstream for some time to come. Therefore, it is also necessary to improve the thermal efficiency of ICE vehicles.

Nissan has continued its vigorous efforts to improve the efficiency and reduce the environmental impact of ICES without sacrificing the joy and pleasure of driving.
Driving, such as by adopting direct fuel injection, variable valve timing, downsizing and turbocharging technologies, among other things. The KR20DDET “Variable Compression Turbo” (VC-Turbo) engine introduced here features a variable compression ratio (VCR) and Downsizing Turbo technologies. This engine has been newly developed to achieve both dynamic performance and environmental performance simultaneously at the highest possible levels. The concept of VCR has been around for a long time, but Nissan is the world’s first manufacturer to successfully incorporate this concept in a mass-produced engine that is mounted on the latest generation of the INFINITI QX50.

2. Development Aim of VC-Turbo Engine

The theoretical thermal efficiency of an engine increases with a higher compression ratio, thereby making it possible to improve its fuel economy (Fig. 1). However, raising the compression ratio tends to cause engine knock and excessively high cylinder pressure. Consequently, the compression ratio of actual engines is restricted by the knock limit and allowable cylinder pressure limit at full load, which is the most severe operating condition. Under part load operation, on the other hand, the pressure and temperature of the burned gas in the cylinder are lower, which allows leeway for raising the compression ratio in relation to the occurrence of knock and the allowable cylinder pressure. Accordingly, adopting a variable compression ratio (from 8:1 to 14:1 with this system) would make it possible to set the optimal compression ratio for each operating condition, which would improve both thermal efficiency and power (Fig. 2). For turbocharged engines in particular, for which there is a tendency to set a lower compression ratio, this would allow the compression ratio to be set equal to or higher than that of naturally aspirated (NA) engines for operation in the non-turbocharged region.
The combination of a turbocharged engine and VCR would be highly advantageous, resulting in the attainment of greater benefits. This thinking was the motivation for developing the VC-Turbo engine.

Table 1 lists the main specifications of the VC-Turbo engine. To maximize the benefits of VCR, the engine incorporates a host of advanced technologies, including electric valve timing control (VTC), a wide-range turbocharger with an electronically controlled wastegate, a direct and port fuel injection system, and a variable displacement oil pump, among others (Fig. 3).

### 3. Nissan VCR Mechanism

#### 3.1 Configuration of multi-link crankshaft rotation mechanism

In this VCR engine, Nissan’s unique multi-link crankshaft rotation mechanism replaces the conventional piston-crank system (conventional system). Similar to the conventional system, this unique mechanism still has the piston and crankshaft, but they are connected in tandem by two links, namely, upper link (U-link) and lower link (L-link), instead of by a conventional connecting rod, as shown in Fig. 4. One end of the L-link is connected to control link (C-link) and control shaft. The rotational orientation of the eccentric control shaft is controlled by an electric actuator via actuator link (A-link). In the case of an inline multi-cylinder engine, each cylinder is provided with a piston, U-link, L-link and C-link, but the crankshaft and control shaft are shared in common by all the cylinders (Figs. 4 and 5).
Operating principle of VCR mechanism

The rotational orientation of the control shaft changes in the clockwise direction in relation to the engine block. When the eccentric control shaft, i.e., the swivel point of the C-link moves downward, the L-link turns in the clockwise direction around the crank pin. The included angle of the U-link and the L-link increases at top dead center and the U-link and the piston move upward, enabling the mechanical compression ratio of the engine to be raised. Conversely, when the rotational orientation of control shaft is changed in the counterclockwise direction, the mechanical compression ratio can be lowered. In the case of an inline multi-cylinder engine, one control shaft is shared by all the cylinders. Accordingly, the mechanical compression ratio in all the cylinders can be changed simultaneously by the change in the rotational orientation of the single control shaft relative to the engine block (Fig. 5).

Electric actuator for compression ratio control

The rotational orientation of the control shaft can be maintained or varied according to the engine operating conditions via an actuator for compression ratio control, as shown in Fig. 6. The actuator assembly combines an electric motor and a reduction gear and is provided separately from the multi-link crankshaft rotation mechanism described above. It is attached to the outer surface of the oil pan side wall. The compression ratio control actuator is connected to the control shaft via the A-link; it reduces the rotational motion of the electric motor, which is controlled by the engine control unit (ECU), and controls the rotation of the control shaft. A newly designed Harmonic Drive® reduction gear has been adopted that achieves a high reduction ratio in a compact space and also has very little backlash.

Distinctive piston stroke

The multi-link crankshaft rotation mechanism has features not found in a conventional piston-crank system. Compared with the conventional system, the piston stroke motion resembles simple sine wave, thereby enabling a substantial reduction of the second-order vertical excitation force that tends to be augmented in an inline 4-cylinder engine. In general, the piston motion in the conventional
Development of the New KR20DDET VC-Turbo Engine with World’s First Variable Compression Ratio Technology

3.5 Friction characteristic

The multi-link crankshaft rotation mechanism has an additional feature. That is, the U-link positioned directly below the piston maintains nearly an upright orientation during the piston’s downward stroke. This greatly reduces the side thrust force on the piston ordinarily induced by the tilting of a conventional connecting rod when combustion force pushes downward on the piston. As a result, friction between the piston side wall and the cylinder bore is significantly reduced. The effect of reducing friction caused by the side thrust force offsets the increase in friction due to the larger number of sliding surfaces of the bearings in the multi-link mechanism. As a result, it achieves a friction characteristic equal to or even lower than that of a conventional system without second-order balancer shafts.

4. Technologies for Improving VC-Turbo Engine Performance

4.1 Improvement of fuel economy

The compression ratio of conventional fixed compression ratio engines has been raised to attain peak thermal efficiency. However, as the compression ratio is increased, the ignition timing tends to be more limited by system is very fast near top dead center, whereas it is slow near bottom dead center. It is known that this absolute difference in piston acceleration between top and bottom dead center causes second-order inertial vibration. The multi-link crankshaft rotation mechanism markedly reduces this absolute difference in the piston’s acceleration compared with that of the conventional system. (It is reduced to approximately one-tenth of that of a conventional Nissan system having an identical piston stroke length.) As a result, it eliminates the need for a second-order balancer system that is often used as a countermeasure against booming noise in the passenger compartment of vehicles equipped with an inline 4-cylinder engine having a conventional piston-crank system (Fig. 7).

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能であり、非過給領域では高圧縮比設定として高圧縮比NAエンジンに比べてピーカーを高めつつ、高負荷の過給域にかけて徐々に圧縮比を下げていくことでピーカーを求め、かつ過給域まで含む広範な良燃費領域を得ることができた（図9）。

4.1.1 圧縮比の設定

ここでは、実際の圧縮比マップの設定事例とその考え方を紹介する。圧縮比マップは、解析と実機検証を元に、主に以下3領域に着目点を置いて設定した（図10）。

- 低速かつ低負荷なる、一般的な走行において使用頻度が高い領域は、最良燃効を得られるように高圧縮比側を設定
- 非過給から過給への遷移領域は、非過給時トルクが最大限確保可能となる圧縮比を選定
- 高負荷領域は、過給下における最良燃効を得られるように低圧縮比側を設定
- 高速かつ低負荷領域は、ドライバーがこの領域を使う意図を考慮し、ターボラグとトルクレスポンスに優れた中～低圧縮比に設定

4.1.2 電動VTCの採用

本エンジンの低負荷領域では、VCRの採用で使えるようになった機械圧縮比14を最大限活用するべく、ハイブリッド車用エンジンに多く見られるアトキンソンサイクルを狙い、下死点後110度のクランク角度のIVC（Intake Valve Closing）遅角バルブタイミング設定とし、ボンビングクビ度を極小化で高燃効率改善を行っている。このために従来よりもバルブタイミングの変換範囲は大きくなる。また、車両を加速させる際には、このIVC遅角バルブタイミングから高負荷領域のバルブタイミングへの応答速度がトルクレスポンスに直結することになる。そこで従来の油圧式に比べて応答速度の遅い電動VTC（eVTC）を採用し、IVC最遅側状態からであっても十分なトルク

the occurrence of knock during high load operation, thus restricting the region of good fuel economy to the low load side. For this reason, it has been necessary to determine an acceptable compromise point for this trade-off when designing conventional fixed compression ratio engines. With VCR engines, this trade-off can be overcome by setting a high compression ratio in the non-turbocharged region to obtain higher peak efficiency equivalent to that of a high compression ratio NA engine; the compression ratio is gradually lowered in the high load turbocharged region to obtain peak efficiency. This achieves good fuel economy over a wide operating range that includes the turbocharged region (Fig. 9).

4.1.1 Setting of compression ratio

This section presents an example of an actual compression ratio map defined for the VC-Turbo engine and the thinking behind it. The compression ratio map shown in Fig. 10 was defined with primary emphasis on the following operating regions based on the results of a simulation and experimental validation.

- The compression ratio is set on the high side in the operating region frequently used in ordinary driving at low speed and low load so as to obtain the best thermal efficiency.
- In the region of a transition from non-turbocharging to turbocharging, the compression ratio is selected so as to maintain the maximum attainable torque of non-turbocharged operation.
- The compression ratio is set on the low side in the high load region so as to obtain the best thermal efficiency during turbocharging.
- In the region of high speed and medium to low load, a medium to low compression ratio is set that is optimal for turbo lag and torque response, considering the driver’s intention to use this operating region.

4.1.2 Adoption of electric VTC system

The adoption of VCR technology enables the use of a mechanical compression ratio of 14:1 in the low load region of the VC-Turbo engine. To maximize the effect of this compression ratio, the intake valve closing (IVC) timing is retarded to a crank angle of 110° after bottom dead center with the aim of using the Atkinson cycle as is...
Development of the New KR20DDET VC-Turbo Engine with World’s First Variable Compression Ratio Technology

4.2 High output and high response to accelerate the wide range turbo

The turbocharger was designed in consideration of obtaining both high power output of 100 kW/L and quick turbo response in the low speed region. In the high speed region, the low compression ratio allows leeway with respect to the limitations on the ignition timing and the exhaust gas temperature. That makes it possible to increase charging efficiency to a corresponding extent, which allows high boost pressure of approximately 260 kPa (abs) and enables the VC-Turbo engine to achieve higher output of 200 kW.

Designing the turbine with a high flow rate characteristic generally results in a larger size that often degrades response. A mixed-flow turbine was adopted to obtain both high output and quick response. The U/C0 characteristic, where U is the turbine rotor inlet peripheral speed and C0 is the adiabatic theory flow rate, was optimized as the speed ratio in the low flow rate region to improve turbine efficiency in the low speed range. This also made it possible to achieve lower inertia for improving boost response in the low speed region.

The compressor wheel was also designed for obtaining both high maximum output and quick torque response in the low flow rate region by taking into account the compressor’s wider range of adiabatic efficiency. Care was taken to keep the point where the compressor does maximum work, i.e., the point of maximum engine output, within 65% of the compressor’s adiabatic efficiency. At the same time, the surge line was widened toward the low flow rate side by designing a small compressor trim size.
レベルを達成し（図14）、最大出力と発進レスポンスを両立させ、高速道路の進入時や追い越しシーンでストレスなく1ランク上の余裕の走りを実現させることができた。

5. VCターボ達成性能

新型VCターボエンジンは、VCRと上記で述べた主要技術によって、図15に示す出力特性を達成する。また本エンジンを搭載する新型INFINITI QX50の車両燃費性能および動力性能の両方においてペンチマークレベルを達成することができた（図16）。

6. まとめ

以上のように、新型VCターボエンジンは世界初の量産型VCR機構と様々な技術との組み合わせにより、ダウンサイズターボエンジンの動力性能を向上させつつも、燃費性能を飛躍的に向上させることができた。本エンジンが自動車の持つ、走ることの楽しさ・喜びを損なうことなく、

i.e., the ratio of the impeller inlet diameter to its outlet diameter, which is the factor that determines the compressor efficiency characteristic. Additionally, the shape of the housing was aerodynamically optimized. As a result, a wide-range compressor was achieved that improves the corrected mass flow rate per unit width by approximately 20% from the surge line to 65% adiabatic efficiency at a compressor pressure ratio $\pi_c = 2.0$ in comparison with the compressor efficiency map for an existing 2.0L class turbo engine model A (Fig. 13).

Design optimization of the turbine and compressor characteristics achieved the benchmark level defined for the output vs. intercept point (Fig. 14). The maximum engine output and acceleration response thus obtained provide a performance one level higher for stress-free driving in expressway entry and passing situations.

5. Performance Achieved by VC-Turbo Engine

The new VC-Turbo engine achieves the power and torque characteristics shown in Fig. 15, thanks to the VCR system and the principal technologies described above. In addition, the new INFINITI QX50 mounted with the
Development of the New KR20DDET VC-Turbo Engine with World’s First Variable Compression Ratio Technology

VC-Turbo engine attains the benchmark levels set for both vehicle fuel economy and power performance (Fig. 16).

6. Conclusion

As described here, the new VC-Turbo engine combines the world’s first mass-produced VCR mechanism and a host of advanced technologies to dramatically improve fuel economy while also enhancing the power performance of a downsized turbo engine. We are confident that this engine can contribute to the sustainable society by playing an important role in reducing the environmental impact, without sacrificing the pleasure and joy inherent in driving a vehicle.

Finally, the authors would like to thank everyone involved inside and outside the company for their invaluable cooperation with research and development of the VCR system extending over 20 years from its conceptualization and with the commercialization of the VC-Turbo engine.

7. References

1. Introduction

Nissan led other automakers in introducing the world’s first mass-market electric vehicle (EV) when it launched the first-generation Nissan LEAF in 2010. Since then, the Nissan LEAF has been marketed in 48 countries worldwide and has been favored by more than 270,000 customers. Their cumulative driving distance totals some 3.4 billion km, and there has not been even a single serious incident caused by the battery. This stellar record attests to the high reliability of Nissan’s EV technologies.

The first-generation Nissan LEAF has also enjoyed an exceptionally high degree of satisfaction among customers. It boasts the highest ratings among Nissan vehicles especially with regard to acceleration performance and quietness.

As the second-generation model, the new Nissan LEAF (Fig. 1 and Table 1) inherits the impressive achievements of the first generation and is intended to further penetrate Nissan EVs and to make the company’s EV leadership well-established. It has been developed as a vehicle to symbolize Nissan Intelligent Mobility.
2. 商品コンセプト

新型ディスプレイを開発するにあたり、様々な方向性のコンセプトが策定された。その中には、徹底的な廉価化による台数の拡大や、航続距離の大幅向上を伴う高品位路線などもあったが、新型ディスプレイのプロジェクトチームは日産のミッションとお客さまからのこのクルマへの期待値という原点に立ち返り、「Driving the Future of Mobility」というコンセプトを設定した。日産のミッションは、手の届きやすい価格で最新技術を提供すること、およびEVをより主流のクルマへ推し進めることであり、そして新型ディスプレイへのお客さまの期待は、未来のモビリティが現実になったと実感できるクルマに乗りたいということである。

そのようなお客さまは、三つの特徴を持っていることが分かった。
① 生活をより良くするために、最新技術を使った製品もんで活用する
② 何かを犠牲にすることは好まないが、より良い社会の実現に貢献したいと思っている
③ 楽しくエキサイティングな運転経験をEVに期待している

そこで、このようなお客さまをProgressive Thinkers（先進的で賢く使えるものを選ぶお客さま）と名付け、お客さまの毎日の生活にEVのある新しいライフスタイルを提供することのできるクルマとして、新型ディスプレイを開発することとした。

3. アピールポイント

3.1 航続距離の向上

EVの購入を検討されるお客さまの心配事のひとつは航続距離である。そこで、新型ディスプレイではバッテリー容量を拡大し、JC08モードで400kmの航続距離を実現している。北米および欧州向けはそれぞれEPAモードで150mile、NEDCモードで378kmである（北米および欧州向けは認証取得中のため仮値）。

一般的なガソリン車のお客さまでは1日100km以下の方が多いので、安心してEVを使っていただける航続距離を確保した。また、ガソリン車のお客さまの1年の平均走行距離は約12,500km程度で、これを換算すると約240kmであり、平均的な距離を乗るお客さまであれば、新型ディスプレイは1週間に1度の充電で済ませることが可能である。加えて、わずらわしさガソリンスタンドに行く手間も省くことができるのである。

3.2 EVドライビングの楽しさの向上

EVによるクイックでスムーズな加速と高い静音性は、初代でも高価お客さま満足度を得ていたが、新型ディスプレイではさらにそのEVドライビングの楽しさを向上させるため

2. Product Concept

In the process of developing the new Nissan LEAF, various concepts for the direction of vehicle were debated. They included the idea of expanding the sales volume by thoroughly lowering the price and the idea of pursuing an upscale direction by dramatically improving the driving range. However, the project team for the new Nissan LEAF selected “Driving the Future of Mobility” as the concept, going back to the starting point represented by Nissan’s mission and the expectations of customers toward the vehicle. Nissan’s mission is to provide cutting-edge technologies at readily affordable prices and to promote EVs toward being more mainstream vehicles. Customers’ expectations of the new Nissan LEAF include a desire to drive a vehicle that truly feels like it already embodies future mobility.

Our research revealed that such customers have three distinguishing characteristics.
(1) They willingly use products incorporating the latest technologies in order to make their lives better.
(2) While they do not like to sacrifice anything, they want to contribute to building a better society.
(3) They expect an enjoyable and exciting driving experience from EVs.

Therefore, we call such customers “progressive thinkers” who select advanced products that can be used wisely. We decided to develop the new Nissan LEAF as a vehicle that would enable them to enjoy new lifestyles based on an EV in their everyday lives.

3. Appealing Features

3.1 Improved driving range

The driving range is one anxiety that customers have when considering purchasing an EV. The battery capacity of the new Nissan LEAF was increased to attain a driving range of 400 km under Japan’s JC08 emission test mode. Models sold in North America and Europe achieve a driving range of 150 miles under the EPA emission test mode and 378 km under the New European Driving Cycle (NEDC), respectively. (These figures are provisional as the vehicles are still undergoing the homologation process.)

The new Nissan LEAF ensures a driving range that will give even owners of ordinary gasoline vehicles peace of mind about driving an EV because approximately 80% of them drive less than 100 km a day. In addition, owners of gasoline vehicles drive approximately 12,500 km a year on average. Converting that distance to a weekly basis results in a figure of approximately 240 km. For people who drive the average annual distance, charging the new Nissan LEAF only once a week would suffice. Moreover, they would also avoid the hassle of having to make a specific trip to a gasoline station.

3.2 Enhanced EV driving pleasure

The first-generation LEAF enjoyed a high degree of customer satisfaction for its quick, smooth acceleration
に、モータ出力を初代の80kWから110kWへと向上させ、走り出しの加速だけでなく、中速域からの再加速性能も向上させている。

これに新開発のe-Pedalを組み合わせた。e-Pedalとは、アクセルペダルの踏み加減を調整するだけで加速、加速、減速、停止までをコントロールすることができる機能である。瞬時に加速するときはアクセルペダルを強く踏み込み、ゆるめればブレーキを踏んだように確実に減速し、さらにクルマを停止、保持する。緊急時や、より強い減速が必要な場合にはブレーキペダルを踏む必要があるが、ストップ&GOを繰り返す街中ではブレーキペダルへの踏み替え頻度が減って楽に運転することができ、一方、ワインディングなどでは思い通りの加減速によってスポーティなドライビングを楽しむことができる。また、雪道などの滑りやすい路面でのアクセル操作にも効果的で、安定した運転も可能になるという特徴もある。この機能によって110kWに出力を向上した新型日産リーフの走りをしっかり楽しむことができる。もちろんe-Pedalは全車標準装備であるが、お客様の好みや用途に応じてON/OFFを切り替えこともできる。

3.3 EVならではの室内静粛性の向上

新型日産リーフにはエンジンが無いため、ガソリン車に対して根本的に静粛性が高いが、静粛性が向上するとタイヤと路面との音が生じるロードノイズや、高速走行時には風切り音が気になる。そこで、外からの音の侵入を絶対的に防ぐための設計、および吸音材と構造の最適化技術で高さ音を低減し、欧州プレミアムブランドのEセグメントと同等の室内静粛性を達成している。

3.4 使える先進技術装備

既に日本市場向けのセレナおよびエクストレイルに搭載し、お客様から好評を得ている高速道路等同車線内自動運転技術プロパイロットを新型日産リーフにも搭載した。新型日産リーフならではのスマートな加減速や高い室内静粛性とプロパイロットの組み合わせにより、今までのクルマにない非常に快適な移動空間を実現している。これがEV技術と自動運転技術の親和性が高いと言われている理由である。

また、お客様が日常的にわずらわしいと感じるシーンとして代表的な「駐車」に関しても、日産の自動運転技術を使ったプロパイロットパークを日産初採用した。これは簡単な操作で、駐車できるポイントをクルマが見つけてドライバーにお知らせするとともに、ドライバが駐車する位置を選んだ後、ステアリング、アクセル、ブレーキ、シフトチェンジ、パーキングブレーキまでをクルマが自動で制御し、選択した駐車位置に入れるところまですを実施する

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3.4 Enhanced interior quietness characteristic of EVs

Because the new Nissan LEAF does not have an engine, it is intrinsically much quieter than gasoline vehicles. As interior quietness is improved, road noise produced between the tires and the road surface and wind noise in high-speed driving become more noticeable. Therefore, the body of the new Nissan LEAF was meticulously designed to thoroughly eliminate gaps that serve as paths for the incursion of outside noise. Additionally, technologies for optimizing sound-absorbing materials and structures were applied to develop a body with high sound-insulation performance. The new Nissan LEAF provides interior quietness equal to that of European premium-brand vehicles in the E-segment.

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**図-2 プロパイロットパーキング**
Fig. 2 ProPILOT Park
3.4 Usable equipment with cutting-edge technologies

The new Nissan LEAF features ProPILOT autonomous driving technology that is used during single-lane highway driving. This technology is already provided on the Serena and X-Trail models for the Japanese market and is highly popular with customers. The smooth acceleration and exceptional quietness that characterize the new Nissan LEAF are combined with ProPILOT to create extraordinarily comfortable mobility never before seen in vehicles. This is one reason why EV technology and autonomous driving technology are regarded as having such high affinity.

The new Nissan LEAF also comes with ProPILOT Park, a Nissan-first feature that makes use of the company’s autonomous driving technology. This feature assists customers with parking, which is a typical example of a driving situation that they ordinarily feel is a hassle. This function begins with the vehicle finding and informing the driver of a place to park as a result of a simple input operation. After the driver selects the position for parking, ProPILOT Park automatically controls the steering wheel, accelerator, brake pedal, shift lever changes and even the parking brake to guide the vehicle into the selected parking spot. The driver can optionally select not only reverse parking, but also parallel parking and forward parking (Fig. 2). The forward parking capability is especially important because the charging port on the new Nissan LEAF is located at the vehicle front. ProPILOT Park differs from other similar systems that are based solely on sensors. In addition to 12 ultrasonic sensors mounted on the vehicle, it also has four high-resolution cameras located on the right and left sides at the front and rear. Camera images are used to detect white lines on a cark park floor. This makes it possible to position the vehicle properly in one parking space in cases where two adjacent parking spaces are open.

3.5 Design

The exterior design of the new Nissan LEAF is based on that of the IDS Concept (Fig. 3) that Nissan announced in 2015. The IDS Concept represented a future vision of Nissan Intelligent Mobility. In other words, it anticipated that the production model of the new Nissan

![Fig. 3 Nissan IDS Concept](image-url)
LEAF would symbolize Nissan Intelligent Mobility.

The key theme of the exterior design is a “cool tech attitude.” It combines both dynamic styling suggestive of exhilarating driving performance and excellent aerodynamics for maximizing the driving range. It embodies distinctive design elements of the Nissan brand such as the V-motion grille, signature boomerang-shaped headlights, floating roof and kick-up waist line. In addition, the unique flush-surface grille with a captivating clear blue layer effect and the rear bumper’s blue molding serve as identifying EV icons (Fig. 4).

The theme of the interior design (Fig. 5) is the coexistence of a relaxing ambience and a cool, high-tech look. The design approach emphasized high perceived quality that eliminates unnecessary decoration, with the display, switches and other controls positioned so as to allow smart ease of operation.

4. Conclusion

The new Nissan LEAF is not merely a new generation of an EV. Rather, it embodies the concept of Nissan Intelligent Mobility and is a product that can propose new lifestyles to customers through its use.

Intelligent Power is given concrete expression in exciting EV driving achieved through battery technologies that improve capacity and extend the driving range and through motor and inverter technologies that boost power output. Another key technology supporting Intelligent Power is e-Pedal that facilitates a novel driving style one would expect from the new Nissan LEAF. Intelligent Driving is distinctly exemplified by ProPILOT and ProPILOT Park technologies that are provided on the new Nissan LEAF.

Nissan’s mission is to continue to provide customers with such cutting-edge technologies at readily affordable prices and to lead the future of mobility for the sake of our customers. The new Nissan LEAF is concrete proof that we are actually implementing this mission.

Finally, the author would like to thank everyone involved, including the R&D, design, manufacturing, marketing, sales and other divisions, for making it possible to announce and release with the new Nissan LEAF with perfect timing amid the marked shift to EVs in the global vehicle market.
1. Introduction

Premium midsize sport utility vehicles (SUVs) account for approximately 50% of the total premium segment demand in the U.S. and China, where annual vehicle sales in this category are around 500,000 units in each market. European premium brand models typified by the Audi Q5, BMW X3 and Mercedes GLC compete fiercely in this crowded segment. The previous-generation INFINITI EX (J50 model, renamed the QX50 in July 2013) was released in 2007 as the pioneer premium midsize crossover SUV. It has been highly acclaimed and has recorded cumulative sales of 115,000 units. The new QX50 has been developed as a vehicle that embodies the latest INFINITI brand qualities and is fully capable of competing with European premium brand models (Fig. 1).

2. Product Concept

The product concept was defined as an “uncompromising life creator; copilot of your drive in life.” While the new QX50 is targeted at customers in their 30s with a family as a vehicle for making their lives easier and more comfortable, it can also be a personal expression. It was designed around the themes of distinctive proportions and powerful elegance. The QX50 features space efficiency achieved with a new platform, improved dynamic performance, and the world’s first variable compression ratio engine. These features are intended to surpass rival
European premium midsize SUVs in all qualities, including design, power performance, fuel economy, handling, ride comfort and quietness.

3. Appealing Features

3.1 Exterior design exuding “powerful elegance”

The driver’s eye point is set at 1,287 mm above the ground level and large 19-inch or 20-inch wheels, one inch larger than those of rival models, were adopted. These features project a powerful stance befitting an SUV and create distinctive body proportions recognizable at a glance even from a distance (Table 1, Fig. 2). A clamshell hood was adopted together with 4-bar linkage hood hinges, resulting in a unique body side view with the character line continuously running smoothly along the body sides from the front to the rear. It also contributes to making the hood look longer visually. The door waist character line has a cross-section included angle of 125°, the smallest in this class and giving the door cross section a deeply chiseled look resembling sculpture, which imparts a solid impression.

3.2 Interior design featuring advanced human artistry

The interior design was defined based on the concept of “driver-centric, yet passenger-minded.” The layout of the operating controls and display systems was determined in consideration of safety and ease of use for supporting the driver’s operation of the vehicle. Ease of operation from the front passenger’s seat was also taken into account.

The overall interior was designed with the aim of projecting an impression of stellar quality and a handcrafted feeling (Fig. 3). Meticulous care was taken in choosing and refining the materials based on the principles of selection and tailoring so as to incorporate Japanese delicate sensitivity. Many areas of the interior are covered with either artificial or real leather, depending on the trim grade, rather than plastic, which, in combination with the stitching, pursues a feeling of authenticity and fine craftsmanship. The wood-grain finishers feature an open-pore material that imparts an impression of natural
3.2 “Advanced human artistry” インテリアデザイン

インテリアの空間は“Driver centric, yet passenger minded”のコンセプトに基づき定義した。操作系、表示系はドライバの運転を支援するために使いやすく、安全性を考慮してレイアウトを決定した。また助手席からの操作性にも配慮をした。

インテリア全体は品質感があり、かつ手芸品を思わせるものを目指した（図3）。“見立て、仕立て”の概念に基づき素材の選択と仕上がりにこだわり、日本的な繊細さを織り込んだ。インテリアの多くの部位を樹脂ではなく、合成皮革もしくはグレードによって本革を張り込み、ステッペと組み合わせにより本物感、工芸品感を追及した。木目フィニッシュには多孔質材料を採用し、自然な本物感を実現した。

最上級モデルの内装にはブルー、ブラウン、ホワイトの特徴的なカラーコーディネーションと人が触れる部位に本革を採用し、上質な本物感を目指した。

3.3 世界初可変圧縮比エンジン VC-T

量産エンジンとしては世界初の可変圧縮比ターボエンジン VC-T (Variable Compression-Turbocharged) を全車に採用した（図4）。圧縮比を可変することにより、直列4気筒2.0Lガソリンエンジンにもかかわらず、V6 3.5Lガソリンエンジン並みの出力と最新20Lディーゼルエンジン並みの燃費を両立させた。マルチリンク機構により、圧縮比は運転状況に応じて8:1 (高性能) から14:1 (高効率) まで連続的に可変させることができる（Fig. 5）。最高出力200kW、最大トルク380Nmを発揮し、燃費はUS combineモードで前輪駆動モデルが27mpg (11.5km/L)、4輪駆動モデルは26mpg (11.0km/L)と、どちらもクラストップを達成している。これはV6ガソリンエンジンに対し35%の改善に相当する。マルチリンク機構の効果として、エンジン回転中にコリオリロッドがほとんど垂直に保たれるためgenuineness.

The interior trim of the top-of-the-line models adopts distinctive color coordination schemes of blue, brown and white as well as real leather trim at places occupants touch, with the aim of projecting an impression of premium quality and genuineness.

3.3 VT-C engine—world’s first with variable compression ratio

All models are equipped with the VC-T engine, the world’s first mass-producible variable compression ratio turbocharged engine (Fig. 4). As a result of making the compression ratio variable, the engine produces power equal to a 3.5L V6 gasoline engine, despite being a 2.0L in-line 4-cylinder unit, while also providing fuel economy equivalent to that of the latest 2.0L diesel engines. The multi-link mechanism continuously varies the compression ratio to match the engine operating conditions, ranging from 8:1 for high performance to 14:1 for high efficiency (Fig. 5). The engine produces maximum power of 200 kW and maximum torque of 380 Nm. Front-wheel-drive models achieve fuel economy of 27 mpg (15.5 km/L) and four-wheel-drive models provide 26 mpg (11.0 km/L) under the U.S. combined city/highway test cycle. Both figures represent class-leading fuel economy and correspond to a 35% improvement over the previous V6 gasoline engine. An auxiliary benefit of the multi-link mechanism is that the connecting rods are maintained in nearly an upright orientation during engine operation, which reduces the thrust force applied to the cylinder walls. This enables the engine to operate with notable quietness without requiring balancer shafts.

3.4 New platform

The new QX50 is built on an all-new platform. One of its distinctive features is that it achieves class-leading packaging efficiency to maximize both interior roominess and luggage area space. The platform was newly developed with the objective of providing handling, stability, ride...
め、シリング壁へのスラスト力が低減されバランス無しで静穏性を確保している。

3.4 新プラットフォーム
新型QX50には、全面新規開発のプラットフォームを採用した。その特徴は、クラスタップレベルのパッケージ効率により室内空間とラジオスペースを最大化すること、欧州プレミアムブランドクラスの競合車と同等以上の操安性、乗り心地、ハンドリング、静穏性、安全性の実現、および軽量化を目的に開発した。

大型ベビーカーが前後方向に積載できるようにラジオの前後長は990mmを確保し、競合車に対する強みとした。

リヤシートには150mmストロークのスライド機能を採用し、フレキシブルに後席とラジオを活用できる。

自動車業界の高成長性980MPaハイテンスをフロントおよびリヤのクラッシュプルダウンに採用することにより、効率よくエネルギーを吸収できる構造とした。ハイテンスの適切な配置と二重軸管ボディ構造によるボディ後部およびラジオ開口部の剛性アップにより、前線比*23%のねじり剛性を実現し、操安性の向上、振動のキャビンへの伝達低減に寄与することができた。

サスペンションのチューニングは、長距離を運転しても疲れないようスタビリティを重視しながら、操舵の正確さ、快適な乗り心地を高次元でバランスさせた。

3.5 高速道路同一車線内自動運転支援技術ProPILOT Assist
INFINIITIとしては初の高速道路同一車線内自動運転支援技術であるProPILOT Assistを採用した。これは将来の自動運転技術への橋渡しの一歩となるものである。新型QX50のシステムの特徴は、DAS（Direct Adaptive Steering）と組み合わせたことにある。通常のステアリングシステムに比べ、ハンドルとステアリングシャフトが機械的につながっていないことにより、ステアリング系の慣性質量が小さくなり、直線およびコーナーを走行時に正確なレーンをキープし、かつスムースな動きを実現できる。

4. おわりに
新型INFINIITI QX50は、高効率な新設のプラットフォーム。世界初の技術である可変圧縮比エンジンVC-Tにより白紙の上に理想的なクルマをつくることができた夢みられたプロジェクトである。先代の後継としてではなく、常にお客様の期待を満たすことを目標にしながら、欧州プレミアムミッドサイズSUVと伍（ご）して戦えるクルマ、最新のINFINIITI-nessを体現するクルマとして仕上げることができた。

comfort, quietness and safety equal to or better than rivals in the European premium brand class and also to reduce the vehicle weight.

The luggage area measures 990 mm in length, which is sufficient to accommodate a large baby stroller in the lengthwise direction. This is a prominent feature compared with rival models. The sliding mechanism of the rear seat allows long travel of 150 mm, enabling flexible use of the rear seat and luggage area.

The front and rear crushable zones are made of 980 MPa high tensile strength steel sheet with high formability. This application is a first for the automotive industry and the body structures enable highly efficient absorption of crash energy. The placement of high tensile strength steel sheet at suitable locations and the double tubular body construction increase the stiffness of the body rear end and around the luggage area opening. As a result, torsional stiffness is 23% higher than that of the previous model, which contributes to improving handling and stability and to reducing the transmission of vibration to the cabin.

The suspension has been tuned to provide an optimum balance of steering accuracy and pleasant ride comfort, while emphasizing stability so as to avoid driver fatigue even on long-distance drives.

3.5 ProPILOT Assist for autonomous driving support in the same expressway lane
The new QX50 is the first INFINIITI model to adopt ProPILOT Assist, a Nissan technology supporting autonomous driving in the same expressway lane. This system is intended to be an in-between step toward autonomous driving technology in the future. A distinctive feature of this system on the new QX50 is that it is combined with Direct Adaptive Steering (DAS). Compared with a conventional steering system, the steering wheel and the steering shaft are not mechanically connected. This reduces the inertial mass of the steering system, which enables accurate lane-keeping when driving straight ahead or cornering and also ensures smooth vehicle motions.

4. Conclusion
The new INFINIITI QX50 was a highly successful project that created an ideal vehicle from a blank drawing board, thanks to the newly developed platform with high efficiency and the VC-T engine incorporating the world’s first variable compression ratio technology. The goal set for the new QX50 was to respond to customers’ expectations at all times without simply continuing the previous model. The resulting new QX50 is a vehicle that embodies the latest INFINIITI-ness and is capable of competing head-on with European premium brand SUVs.
# 社外技術賞受賞一覧表

## 1. 技術賞

（2016年11月～2017年10月）

※主な技術賞、論文賞、質疑・労労賞を対象に掲載しております。
※所属は受賞時の所属、（ ）は研究開発担当の部署。
※敬称略。

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日産技報 No.82 (2018–3) 72
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（2016年11月～2017年10月）
2. 製品ほか受賞
（2016年11月～2017年10月）
※主要な製品賞を対象に掲載しております。

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・Environment category | Automobile, Motor and Bicycle Association of Austria (ARBÖ) |
| 2016.11  | Sliding door and tailgate of the new Nissan Serena | Doors and Closures in Car Body Engineering  
2016  
・Innovation Award | （独）Automotive Circle |
| 2016.11  | 奥会津・EV移動販売車プロジェクト | KAIKA Awards 2016  
KAIKA賞 | 一般社団法人日本能率協会 |
| 2016.12  | セレナ | 第37回（2016・2017）日本カー・オブ・ザ・イヤー  
・イノベーション部門賞 | 日本カー・オブ・ザ・イヤー実行委員会 |
| 2016.12  | 企業間連携による大型コージェネの排熱的な利用の実現　～日産自動車横浜工場J-オイルミルズ横浜工場間の熱融通事例～  
（東京ガスエンジニアリングソリューションズ株式会社／日産自動車株式会社／株式会社J-オイルミルズ） | コージェネ大賞2016  
産業用部門 優秀賞 | 一般財団法人 コージェネ財団 |
| 2016.12  | Kicks | Auto Show TV 2016  
・Diseño Más Innovador | （メキシコ）Auto Show TV |
| 2016.12  | Kicks | 10Best award 2016  
・The Best category  
・Melhor (Best) SUV category | （ブラジル）「Car and Driver Brazil」誌 |
| 2017.1   | VR32 GT-R | 東京国際カスタムカーコンテスト2017  
・チューニングカー部門 最優秀賞 | 東京オートサロン事務局 |
| 2017.1   | SKYLINE Premium Sport Concept | 東京国際カスタムカーコンテスト2017  
・セダン部門 最優秀賞 | 東京オートサロン事務局 |
| 2017.1   | Vmotion 2.0 | 2017 EyesOn Design Award  
・Best Concept Vehicle  
・Best Innovative use of Color, Graphics and Materials | （米）North American International Auto Show |
| 2017.1   | Titan | 2017 Pickup Truck of the Year | （米）「Truck Trend」誌 |
| 2017.1   | 3.0L Twin Turbo DOHC V-6 (Infiniti Q50) | 2017 Wards 10 Best Engines | （米）「WardsAuto」誌 |
| 2017.1   | 異業種企業間連携による分散型エネルギーの面的利用の実現  
（東京ガスエンジニアリングソリューションズ株式会社／日産自動車株式会社／株式会社J-オイルミルズ／横浜市） | 平成28年度石油エネルギー大賞  
省エネルギー部会  
省エネルギー効率化会長賞 | 一般財団法人省エネルギーセンター |
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<td>2017上海车展大奖 · 最佳首发新车奖（最高新車賞）</td>
<td>上海国际汽车展览会组委会（上海国際モーターショー）</td>
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<td>2017.10</td>
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<td>2017 Texas Truck Rodeo · Best commercial vehicle category</td>
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1. Introduction

Variable flux permanent magnet synchronous machines (VF-PMSMs) have been proposed to reduce the energy consumption of electric vehicles over a driving cycle. With this type of motor, the magnetization state is varied so as to expand the high efficiency region. Manipulating the magnetization state requires control of the magnetizing/demagnetizing current. However, with the conventional method, the obtainable maximum magnetization state is limited in the high-speed region due to large back electromotive force. In addition, the magnetizing current influences drive axle torque fluctuation.

In this article, the fundamental principle of the straight line stationary flux linkage trajectory (SLST) method, which has been proposed for increasing the obtainable maximum magnetization state in the high-speed region, is clarified by visualizing the spatial magnetomotive force distribution that occurs on the stator at the time of magnetization state manipulation. Experiments and simulations were conducted to investigate the effect of the proposed SLST method when applied to a vehicle traction motor. The results revealed that the desired magnetization state can be achieved in the high-speed region, and drive axle torque fluctuation can be suppressed during magnetization state manipulation.

2. Overview

With the conventional method, the spatial stator magnetomotive force that moves in synchronization with rotor rotation is produced to control the magnetization state. Consequently, back electromotive force is produced that is proportional to the rotational speed and the intensity of magnetomotive force. Because the back electromotive force becomes large in the high-speed region, it is necessary to control the voltage by lowering the intensity of the magnetomotive force. As a result, the obtainable maximum magnetization state has been limited.
Magnetization State Manipulation Method with Low Vehicle Vibration for High Speed Operating Region of Variable Flux PMSMs

In contrast, the SL$^8$T method produces the magnetomotive force that is fixed at an arbitrary position on the stator, thereby reducing the back electromotive force. As a result, the desired magnetization state can be obtained in the high-speed region (Fig. 1-b). It is noted that torque ripples that originate in the magnetizing current occur in the motor. However, the response of the magnetizing current control is improved by the surplus voltage obtained by reducing the back electromotive force. Therefore, the magnetization state manipulation period becomes shorter than the vehicle response time so the transfer of torque ripples to the drive axle is suppressed.

Figure 2 presents the experimental results obtained when the SL$^8$T method was applied to a VF-PMSM having an output comparable to that of a vehicle traction motor. It also shows the drive axle torque calculated at the time of magnetization state manipulation in a simulation that was conducted using the experimental results. The results show that using the SL$^8$T method makes it possible to obtain the maximum magnetization state even in the high-speed region, and that drive axle torque does not fluctuate during magnetization state manipulation.

3. Conclusion

The magnetization state manipulation method described here resolves one of the principal issues involved in applying a VF-PMSM for vehicle traction. It is expected that this method will contribute to the expanded application ofVF-PMSMs in the coming years.
編 集 後 記

今回の特集は「新型日産リーフの電動パワートレイン」です。2017 年 9 月にワールドプレミアを行った新型日産リーフの電動パワートレインの技術について幅広くお伝えできたかと思います。新型日産リーフは前型に対し、車両価格は抑え置きのまま、航続距離や動力性能を向上し、さらに新しい機能を追加して新しい魅力をアピールしていますが、その技術は初代日産リーフが開発した技術を土台として、要素技術を積み重ね、市場走向から得られた新たなデータをフィードバックして開発されたものです。またお客様の要求を高い次元で満足できるよう、お客様から頂いた多数の反響をもとに、新しい目標を設定して取り組んできた技術として読んで頂けると、編集委員として大変嬉しく思います。

電気自動車（EV）そのものの起源は意外に古く、内燃機関と同等の 100 年以上の歴史があります。しかし EV としての技術が目覚ましく発達したのは最近のことであり、初代日産リーフの開発が始まり約 10 年前から、現在、そしてこれからが EV の歴史に残る革命の時代と言えば、エンジニアとしてこの瞬間に立ち会っているのは大変幸運なことではないでしょうか。今回の特集が、自動車をとりまく課題を解決すべく、様々な技術開発に日夜チャレンジされている皆様の参考となれば幸いです。

— 日産技報編集委員・小 野 山 泰 —

### 2017 年度日産技報編集委員会

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### 日 産 技 報 第 82 号

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Editorial Postscript

The special feature in this issue focuses on the electric powertrain for the new Nissan LEAF. The articles extensively describe the technologies incorporated in the electric powertrain adopted on the new Nissan LEAF that made its world premiere in September 2017. Compared with the previous model, the new Nissan LEAF features an extended driving range, improved power performance and also additional new functionality to enhance its captivating appeal, while the price has been kept at the same level. The technologies have been developed on the basis of those of the first-generation model and by feeding back vast amounts of data collected in real-world driving to build up the underlying technical fundamentals. As a member of the editorial staff, I will be very happy if readers view the technologies as resulting from efforts made to achieve new targets based on substantial feedback gathered from customers with the aim of satisfying their requirements at the highest possible dimension.

The origin of electric vehicles (EVs) goes back a surprisingly long way, as EVs have a history of over 100 years equal to that of internal combustion engines. However, it has only been in recent years that EV technologies have shown such dramatic advances. Development of the first-generation Nissan LEAF started approximately ten years ago, and the present time and coming years will be age of EV revolution that will go down in history. Considering that, we feel very fortunate as engineers to be able to witness this momentous time. It is hoped that this special feature will be a useful reference to everyone who is constantly undertaking the challenge to develop various new technologies for resolving the issues surrounding vehicles today.

Taichi Onoyama
Member of the Nissan Technical Review Editorial Committee

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EV・HEV システム開発部の梅木です。電気を動力源とする電動車両のさらなる普及のために、日産自動車は様々な「新しい電動化技術」の開発を進めています。従来の技術に加え、新しい技術を搭載した新型日産リーフが、2017年に発売となりました。今回の表紙は100%電気自動車の新型日産リーフの四つの技術的な特徴、(1) 優れたレスポンスと加速感を表すG波形、(2) 減速時の精確なモータ制御によるスムーズな減速感を表すブロック線図、(3) ワンペダルでのイージードライブを表すアクセルペダル、(4) 40kWh バッテリーと110kW モータを搭載し e-Pedal で停止保持可能な30% 勾配（約16度）を走るスケルトンの日産リーフを組み合わせたデザインとしました。

Nissan is pushing ahead with the development of various new electrification technologies in order to further popularize electrified vehicles that use electricity as their power source. The new-generation Nissan LEAF that was released in 2017 is equipped with many new technical features in addition to existing technologies. The cover design this time expresses four key technical features of this all-electric new Nissan LEAF together with a cutaway view of the vehicle in motion. The features represented are: (1) an acceleration waveform indicating superior response and acceleration performance, (2) a block diagram depicting a feeling of smooth deceleration achieved by accurate motor control during vehicle deceleration, (3) an accelerator pedal that symbolizes the driving ease obtained with one-pedal vehicle operation, and (4) a 30% (approximately 16°) slope on which the e-Pedal system, combining a 40-kWh battery and a 110-kW motor, can stop and hold the vehicle.

梅木 志保
Shiho Umeki
EV・HEV システム開発部
EV and HEV System Engineering Department