NISSAN e-POWER: 100% Electric Drive and Its Powertrain Control

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Nissan has developed a 100% electrified powertrain system called e-POWER, which exhibits key features such as quick response, smooth acceleration, smooth deceleration, and quietness. The quick response and smooth acceleration can be achieved owing to the 100% electric motor drive and control strategy that has been adopted from the Nissan LEAF electric vehicle and improved further. The quietness was designed and controlled using power generation control and engine speed control. A driving mode called the e-POWER drive mode was developed using 100% electric deceleration to achieve smooth and efficient deceleration with linearity and controllability.

Keywords: hybrid electric vehicle, electric vehicle, powertrain control, traction control, power generation control

1. Introduction

“Vehicle electrification” is not only a technology of powertrain, but also the key technology for a major turning point that occurs once in a hundred years. In 2010, Nissan launched an electric vehicle (EV) named Nissan LEAF⁽¹⁾, as the first mass-produced EV at a reasonable price. Nissan LEAF is a medium-sized hatch back vehicle that can seat five adults comfortably. The first-generation 2011 model year Nissan LEAF exhibited a maximum traction power of 80 kW and a driving range of 200 km under the JC08 emission test mode in Japan, which could be sufficient to satisfy real-world consumer requirements for daily use. The performance and usability of the Nissan LEAF have been improved at the time of minor model change, to maintain competitiveness⁽²⁾.

The latest model of Nissan LEAF e+, produced in 2020, exhibits a maximum power of 160 kW and a driving range of 570 km in the JC08, 458 km in the worldwide-harmonized light vehicles test cycle (WLTC). One of the distinctive features of Nissan EVs is the smooth, responsive acceleration obtained by the use of the excellent response and controllability of an electric motor. The motor and its control have been developed by Nissan internally and refined for over 10 years as a core technology for electrification. These features can be achieved using a motor current controller (MC) and an electric power train controller called a vehicle control module (VCM). Control technologies have been enhanced to deliver high-power performance without sacrificing smoothness and quickness. This controllability of the electric powertrain provides not only driving pleasure, but also driving ease in daily use, even for inexperienced drivers. This is one of the reasons

the Nissan LEAF gained popularity in the global market.

In 2016, Nissan launched the e-POWER system as a new hybrid system powertrain for compact cars in the Japanese market which could provide the experience of driving an EV with a smooth and quick response, as the core technology of Nissan’s vehicle electrification⁽³⁾. The hybrid system configuration is a series hybrid system, that uses an electric traction motor, inverters, and basic control software adopted from the Nissan LEAF. The 100% electric drive provides the experience of driving an EV. Additionally, the control strategy for power generation can provide EV quietness in hybrid electric vehicles (HEVs). This control system differentiates the e-POWER system from conventional series hybrid systems. Therefore, Nissan Note became top selling-car in the Japanese market, owing to e-POWER system.

This paper introduces a system configuration and control strategy for the e-POWER system. The commonization of components that are modeled on Nissan LEAF exhibits the unique strategy to provide the EV drive experience and improve the development efficiency. Further, this paper can provide insight into the labeling of this hybrid system as “e-POWER” and not just a series hybrid.

2. System Configuration

2.1 Line up of e-POWER In 2016, the e-POWER system was installed in the Nissan Note model in the Japanese market. The Nissan Note model, shown in Fig. 2, is a compact hatchback model and is the first model to use the e-POWER system. The Nissan Note model also has four-wheel drive (4WD) version which uses an electric motor for the rear axle⁽⁴⁾. The e-POWER system has been incorporated in the Nissan Serena model, a popular minivan in the Japanese market, since March 2018. In 2020, the Nissan Kicks model, a compact sports utility vehicle (SUV), adopted the e-POWER system for the Japanese and Thai markets. In November 2020, the New Nissan Note e-POWER was introduced. This paper focuses on the fundamental of the e-POWER system used for the Nissan Note model in 2016.

2.2 System Configuration The e-POWER hardware

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Fig. 1. Nissan LEAF EV

Fig. 2. Nissan Note e-POWER

Fig. 3. System configuration of the e-POWER

configuration is categorized as a series-hybrid system. The distinctive feature of this configuration is that the power generation system is mechanically separated from the traction system. This means that an internal combustion engine (ICE) is connected to the generator through the transaxle and is not connected to the traction drive-shaft. Owing to this feature, the traction drive system can be adopted from the technology and components used for EVs, and the vehicle is propelled by the electric motor only. The operational torque and speed of the ICE can be set flexibly, and is not dependent on the vehicle traction conditions.

Figure 3 shows the system configuration of the e-POWER. The powertrain system consists mainly of a traction motor (e-Motor), generator, inverters, ICE, and a Li-ion battery.

The traction motor and its inverter which are used in the Nissan LEAF, were adopted. The power generating system incorporates a 3-cylinder, 1.2 L gasoline-powered ICE (HR12DE), which is also used for B-segment ICE vehicles, in combination with a generator with a maximum power

Table 1. Specifications of the e-POWER system used for the Nissan Note (2016) model

Drive System	Traction motor (e-Motor)	Max. Power [kW]	80
		Max. Torque [Nm]	254
Generating System	Generator	Max. Power [kW]	55
		Max. Torque [Nm]	108
	ICE	Model	HR12DE
		Type	Gasoline
		Displacement [cm ³]	1198
		Number of cylinders	3
		Max. Power [kW]	58
Max. Torque [Nm]	103		
Battery		Type	Li-ion 80 cells
		Capacity [kWh]	1.47

output of 55 kW. The transaxle incorporates two functions in a single housing unit. One is a speed-reducing function for connecting the motor and the drive-shaft, and the other is a speed-increasing function for connecting the generator and the ICE. The Li-ion battery is capable of producing a high rate of discharge and charge power, and can deliver a quick acceleration response similar to that of EVs. The water-cooling system for the electric motor, generator and inverters is a dedicated cooling circuit that is not connected to the ICE cooling system. There is a dedicated forced-air cooling system for the Li-ion battery pack. The e-POWER system is controlled by a VCM that communicates with an MC, a generator controller (GC), a battery management system (BMS) and an engine control module (ECM). The function of the GC is similar to that of the MC, which controls the motor current and generates pulse width modulated (PWM) signals for the gate drives of the switching device. The ECM controls and directs the ICE torque to follow the torque command of the VCM. The rotational speed of the ICE is controlled by the GC and the generator to follow the rotational speed command of the VCM. The major specifications of the e-POWER system for the Nissan Note model, which is the first application of the e-POWER system, are listed in Table 1. For other vehicles, the system power and motor torque are designed to satisfy the requirements of a minivan and an SUV.

2.3 Package on a Vehicle Figure 4 shows the in-vehicle layout of the e-POWER including the battery used for Nissan Note model. The drive and power generating systems are integrally assembled. Additionally, the drive and generating systems are functionally separated. As a result, this sub-assembly ensures mountability on compact platforms, such as those of B-segment vehicles. The battery was designed in a compact package, enabling it to be located below the front seats. Positioning the battery pack in the dead space below the front seats enables the possibility of achieving virtually the same cabin space and luggage area as those in an ICE vehicle without affecting occupant comfort. In addition, this battery pack is located around the center of the gravity of the vehicle. Thus, it can contribute to better handling and stability of the vehicle.

2.4 Electric Powertrain of e-POWER The configuration of the e-POWER unit is shown in Fig. 5. The electric traction motor was developed by Nissan, and was adopted from Nissan LEAF. In the Nissan LEAF, these components are connected by three-phase busbars. However, the connection between the inverter and the electric traction motor is

Fig. 4. In-vehicle layout of the e-POWER used for the Nissan Note model

Fig. 5. Configuration of the e-POWER unit

Fig. 6. Traction motor for the e-POWER

designed using three-phase harnesses, to install these components in narrow front space, as shown in Fig. 6. Table 2 shows the specifications of the electric traction motor and generator for the compact car Nissan Note model. The generator can produce enough electric power to satisfy the requirements of maximum acceleration and continuous slope. Additionally, another important function of the generator is that as an engine starter. This power generation system contributes not only a power generation function, but also other functions of providing negative pressure for a mechanical brake system and heating for thermal comfort.

The inverters used in the e-POWER adopt a direct-cooled structure integrated coolant fin. This structure can reduce the thermal resistance between the power devices and coolant; therefore, two inverters can be installed in one box package, as shown in Fig. 7. In addition, the major components

Table 2. Specifications of the traction motor, generator and inverter

	Traction motor	Generator
Max. torque [Nm]	254	108
Max. power [kW]	80	55
Max. speed [min^{-1}]	10500	10000
Outer dimensions [mm] diameter $\times$ length	260 $\times$ 290	210 $\times$ 240
Mass [kg]	52.3	30.2
Inverter (2 inverters in 1 box)		
Max. output current [Arms]	356 (30 [sec])	
	144 (60 [min])	
DC source voltage [V]	240 – 344	
Outer dimensions [mm]	422 $\times$ 406 $\times$ 204	
Mass [kg]	16.9

Fig. 7. Inverter box for the e-POWER

Fig. 8. Total efficiency of the traction motor and the inverter

in the inverter used for the e-POWER are commonly used with the inverter of the Nissan LEAF, for the traction motor. The efficiency of the inverter has been improved by the use of power devices, reduction in inductance and optimization of the drive circuit for power devices. Figure 8 shows the total efficiency of the traction electric motor and the inverter. The optimum efficiency point is approximately 96%, while the average efficiency in the JC08 mode can be more than 92%.

3. System and Control Technology

3.1 Control System Configuration Based on EVs with an electric motor, an inverter, a Li-ion battery and a

Fig. 9. Configuration of the control system for the EV and e-POWER system

Fig. 10. Acceleration at standing start

charger, the control system of the e-POWER system was designed to add an ICE and a generator, to remove the charger. The control system for the e-POWER system was also designed on the basis of that for the Nissan LEAF. The configuration of the control system for the Nissan LEAF and the e-POWER system is shown in Fig. 9. The traction system is adopted from the Nissan LEAF. Thus, the control strategy and software components can be adopted from the Nissan LEAF. Owing to the utilization of the EV traction system and its control, the e-POWER system can achieve a quick and smooth acceleration compared to other HEVs, as observed from the acceleration waveform for the standing start shown in Fig. 10. Hybrid vehicle B uses a parallel hybrid system, and hybrid vehicle A is a competitor's HEV.

3.2 Key Features in Traction System Control Nissan EVs and the e-POWER system have been developed quick and smooth acceleration using the advantage of electric motors with quick response and good controllability. One of the key features of the traction system control is the drive-shaft torsional vibration control. The torsional resonance of the drive-shaft causes a vibration of 9–10 Hz, then, the step input torque of the electric motor causes significant vibration in the drive-shaft and the vehicle. Drive shaft torsional vibration control has been considered on the basis of the modeling of the two-inertia system and the motion equation of the vehicle body⁽⁵⁾⁽⁶⁾. Figure 11 shows the block diagram developed for the Nissan LEAF, where, the feedforward compensator $G_c(s)$ is designed on the basis of the driving torque transmission model and the model of forward/backward motion of the vehicle body. The feedback compensator uses $H(s)$, which is a band-pass filter with a central frequency that coincides with the natural vibrational frequency of the controlled object. Figure 12 shows the experimental results of the drive-shaft torque as a comparison between the step torque command and the drive shaft torsional vibration control. This quick

Fig. 11. System block diagram of the drive shaft torsional vibration control

Fig. 12. Experimental results of the drive-shaft torque for comparison between the step torque command and the drive shaft torsional vibration control

Fig. 13. Energy consumption and power generation balance

and smooth acceleration provides an excellent driving experience, and aids an inexperienced driver with the linearity of the control response. The e-POWER system also uses an improved drive-shaft torsional vibration control.

3.3 System Design for e-POWER Unit and Power Generation Control As concept for the system design of the e-POWER unit is that the e-POWER unit can support 100% EV driving using only energy charged in the battery for typical usage in a real market. The system design for the B-segment vehicle is explained as follows.

In Fig. 13, the circle and triangle symbols indicate the driving mode and typical usage in the Japanese market, such as city, suburban, and Highway (HWY). The system design aims to drive these operating points without engine power generation. However, combined power generation of the battery and the engine is required for high-load situations as

Fig. 14. Scope of EV driving depending on vehicle speed and battery state of charge

Fig. 15. Ratio of engine stop time (EV time) in each vehicle speed range

hill climbing and steep of highway in Japan. This combined power generation can achieve a smooth and powerful acceleration under high-load conditions.

To ensure quietness for the e-POWER system at the same level as that required in an EV, EV driving without power generation is required in a high state of charge (SOC). Further, the power generation is controlled so that the engine noise is lower than the background noise. Figure 14 shows the driving operation of an EV depending on the vehicle speed, acceleration and battery SOC, considering the case of the B-segment e-POWER system. Background noise could be low at low speed and low acceleration. The EV driving is commanded to not start the engine as much as possible. If the SOC is not sufficient to maintain EV driving, the engine can be started at a high speed and high acceleration.

Figure 15 shows the ratio of the engine stop time in each vehicle speed range as a result of real customer usage, including such as highway, suburban and city driving. The results demonstrate an engine stop time of approximately 90% at a low speed in the 0–25 km/h speed, and approximately 50% of the engine stop time at a mid-range speed in the 25–50 km/h speed range. This indicated that a high ratio of EV driving without power generation can be achieved by the e-POWER system design and power generation control, particularly at low and medium vehicle speeds.

Considering the power generation control, the engine revolution speed control shown in Fig. 16 aims to maintain approximately 2400 min^{-1} for better fuel consumption. When high acceleration of the vehicle is required, the engine speed is increased following the vehicle speed acceleration achieved by the generator speed control. In the case of high vehicle speed, the engine speed is controlled to maintain a

Fig. 16. Target engine revolution speed design using vehicle speed and acceleration request

Fig. 17. Operation frequency for real-world fuel economy

high engine speed, because high power is necessary to satisfy the requirement of high acceleration.

To provide better fuel consumption, the VCM can operate such that the ICE can be driven at the optimal fuel consumption point, because of free from drivability constraints. Figure 17 compares the operating point frequency for the real-world fuel economy of the e-POWER system, with that of hybrid vehicle A as another HEV system and HR12DE Conv. (conventional) as an ICE vehicle in the same segment. The contour line shows the efficiency of the HR12DE ICE used in the e-POWER system. The bubble data indicates that the frequency of operation with high efficiency is significantly high for the e-POWER system. This is the key factor for obtaining an excellent fuel economy. In contrast, the data for other HEV system indicates that they tend to lag behind the point of excellent fuel economy when the engine and the motor are operated in parallel because the demanded output power is small at low vehicle speeds. The results indicate that the e-POWER system can improve fuel economy better than the ICE vehicle, based on Nissan's comprehensive evaluation of real-world fuel economy that includes highway, suburban and city driving.

An e-POWER drive mode, called 1-pedal control, has been developed for the e-POWER system as a technique for enabling easy control of the vehicle speed using only the accelerator pedal. This mode provides both good fuel economy and driving pleasure. In addition, the e-POWER system is characterized by its ability to regenerate power at extremely

Fig. 18. Relationship between frequency used in real-world and maximum deceleration by regeneration

low vehicle speeds. This characteristic is a good advantage of the e-POWER drive mode.

Figure 18 shows that the solid line indicating 90% of the necessary deceleration for ordinary driving in the market can be covered by the dotted line indicating the maximum deceleration by regeneration of the e-POWER drive mode. Thus, the frequency of switching from the accelerator pedal to the brake pedal can be reduced by approximately 90%, in typical usage. The e-POWER drive mode also incorporates fine control procedures to enhance its practical utility. As an example, the neutral position for accelerator pedal operation is set at a point where it is unlikely to exhaust the driver, and the distribution of the driving force is centered on this position. Simultaneously, a dead zone is provided in the neutral position as a control measure that easily sustains coasting to improve the fuel economy. The control is also regulated to match the driving situation, to enable smooth deceleration by operating the accelerator pedal even when traveling uphill or downhill. On snowy roads and other surfaces with a low coefficient of friction, the fine-tuned control of the driving force can control the traction motor in all speed ranges. As a result, the deceleration can be controlled to close to the slip limit to enhance drivability.

4. Conclusion

Nissan has developed a 100% electrified powertrain system called e-POWER, which exhibits key features such as quick response, smooth acceleration, smooth deceleration, and quietness. The quick response and smooth acceleration can be achieved owing to the 100% electric motor drive, and control strategy that has been adopted from the Nissan LEAF and improved further. The quietness was designed and

controlled using power generation control and engine speed control. The e-POWER drive mode with 100% electric deceleration achieves smooth deceleration with linearity, controllability and efficiency. Nissan announced that the e-POWER will be launched in the global market in the near future. The 100% electric motor drive used by EVs and e-POWERs will lead the vehicle electrification and solve social issues such as global warming, in addition to providing driving pleasure and enriching people's lives.

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