

A New Hybrid Power Configuration In HEV and Its Driving BLDC Development

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Abstrak

Kendaraan Listrik Hibrid, Hybrid electric vehicle (HEV) yang memiliki keuntungan dari sisi performa yang tinggi, efisiensi bahan bakar yang tinggi, emisi yang rendah serta jangkauan operasi yang jauh telah menjadi fokus penelitian akhir-akhir ini. Suatu konfigurasi daya hibrid yang dipergunakan pada HEV ditampilkan dengan strategi kendali yang berbeda serta performa yang berbeda ketika dilengkapi dengan bahan bakar dan batere yang berbeda. Untuk dapat merelisasikan konfigurasi daya khususnya pada refitted HEV, maka digunakan suatu motor elektrik bertipe fractional-slot concentrated-winding BLDC dengan kecepatan putar yang lebih tinggi. Purwarupa yang dihasilkan telah memenuhi persyaratan performa tinggi dan demission restriction untuk refitted HEV.

Keywords: kendaran listrik hibrid (HEV), konfigurasi daya hibrid, , brushless direct current machine (BLDC)

Abstract

Hybrid electric vehicle (HEV) that has the advantages of high performance, high fuel efficiency, low emission, and long operating range is focused on nowadays. A new hybrid power configuration used in HEV is presented with different control strategies and HEV performances when equipping different weight of fuel power and battery one. In order to realize the new hybrid power configuration especially in the refitted HEV, fractional-slot concentrated-winding BLDC with higher rated spinning speed is given and the prototyped one is developed and fabricated which satisfies successfully the requirements of high performance and demission restriction for the refitted HEV.

Keywords: hybrid electric vehicle (HEV), hybrid power configuration, brushless direct current machine (BLDC)

1. Introduction

Electric traction is one of the most promising technologies that can lead to significant improvements in vehicle performance, energy utilization efficiency, and polluting emissions. Compared with the pure electric vehicle (EV), hybrid electric vehicle (HEV) is the most promising technology that has the advantage of high performance, high fuel efficiency, low emission, and long operating range owing to the existing technology restriction of non-fuel energy storage. A HEV is a trade-off vehicle between a pure EV and an engine vehicle, which use two power sources of fuel and battery plus an electric motor with different weight combinations and structure configurations to power the vehicle [1]. And new hybrid power configurations of HEV emerge continuously. In HEV, It is the electric machine not the engine that is focused on and deeply researched because of the variety of its structure, principle and performance [2].

Based on the brief introduction of the existing hybrid power configuration in HEV, a new one is presented in Section II whose structure, operation modes and superiority are concerned particularly. In Section III, a high-speed fractional-slot concentrated-winding permanent magnet brushless DC machine (BLDC) is introduced to be used in the HEV powered by the presented hybrid power configuration, especially in the refitted HEV, and is studied, designed and fabricated. The prototyped BLDC is given and tested with consequence of good performance and rational structure dimension to satisfy requirements of the refitted HEV when equipping the presented hybrid power configuration.

2. A New Hybrid Power Configuration Used in HEV

Hybrid power system used in HEV can be classified into series one, parallel one and series-parallel one, and every one of which can be evolved into many configurations to satisfy the demanded HEV requirements [1]. A new hybrid power configuration is shown in Figure 1 which consists largely of engine, clutch 1, clutch 2 and electric machine. In the hybrid power configuration, the two shaft ends of electric machine rotor are connected mechanically to engine and reduction gearbox by clutch 1 and 2 respectively. As a result, the starter and the generator which are of necessities in normal engine vehicle are ruled out in the new configuration, that is, the electric machine takes the role of the starter and the generator first. On the other hand, the HEV with this new hybrid power configuration contribute the drive power from engine (fuel) and electric motor (battery) respectively or simultaneously, with the electric machine rotor being used to transform the fuel energy from engine mechanically and battery energy from electrical machine electromagnetically respectively. From this view of point, the new hybrid power configuration belongs to parallel one to some extent, as a result the engine torque and the motor one can exist in many combination modes to realize optimal HEV performance. The HEV equipped with the presented hybrid power configuration features such operation modes as follows if the fuel power dominates compared with the battery one:

(1) When the HEV runs in acceleration or climb mode, the battery power supplies electric motor to yield the additional force to compensate the engine because the HEV equipped with the new hybrid power configuration always features relatively lower engine power compared with the normal engine vehicle. In this running mode, the clutch 1 and 2 are all in releasing.

(2) When the HEV runs in slowing down or brake mode, the electric machine acts as a generator to transform the mechanical energy into electric one which is stored in battery. In this running mode, the clutch 1 holds while the clutch 2 releases.

(3) When the HEV needs a short stop, close the engine to rule out its idle speed while the electric machine runs to prepare to start the engine immediately when in need, or the engine runs to drive the electric machine to generate electric energy.

(4) When the HEV runs in smooth road and in low speed, holds the clutch 1 to close the engine with the electric machine running lonely in motor mode so that the HEV operates in high efficiency compared with the normal engine vehicle.

It can be seen that the HEV with this new hybrid power configuration features such advantages as: (1) A small-displacement engine equipped to achieve the same dynamic capability as the normal engine vehicle with large-displacement engine; (2) A overall high efficiency resulting from no idle engine speed and electric machine's running lonely or additionally; and (3) The simplified and compact structure which is particularly beneficial to the refitted HEV.

As mentioned above, the HEV with this new hybrid power configuration leads to a small-displacement engine and also a small-volume battery with no external charge if the fuel power dominates over the battery. In fact, in this hybrid power configuration, the battery power can dominate over the fuel one with a large-volume battery and external charge inlet, as a result, the fuel power is used only to charge the battery in emergency, leaving a very small displacement engine.

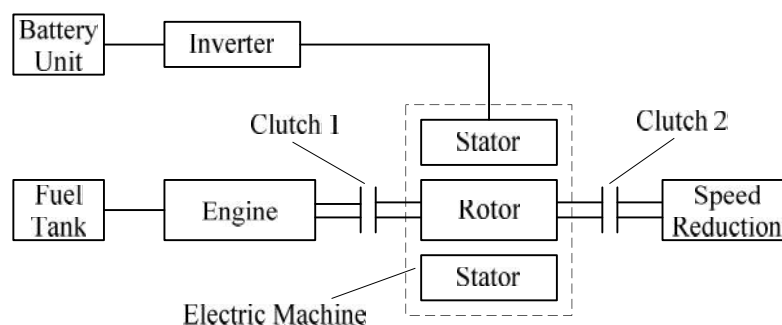


Figure 1. New hybrid power configuration of HEV

The simple and compact structure of this hybrid power configuration makes it find a most potential application in refitted HEV from common engine vehicle. In common engine vehicle, the engine is connected mechanically with the speed reduction through the clutch which is mounted on the flywheel of the engine as shown in Figure 2. From Figure 2, it can be seen that there is a small gap distance between the engine and the speed reduction which can be occupied by a electric machine in the refitted HEV and the electric machine consequently features a large circumference diameter resulting in large inside space to be used to equip the clutch 2 with the original clutch in the engine vehicle being the clutch 1 in the refitted HEV as shown in Figure 3. As a result, the electric machine with special structure of a small axial-orientation length and rational performance requirements is essential to realize this new hybrid power configuration in refitted HEV.

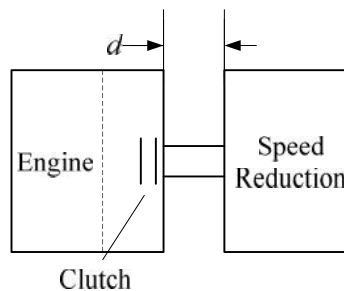


Figure 2. Power configuration in common Engine Vehicle

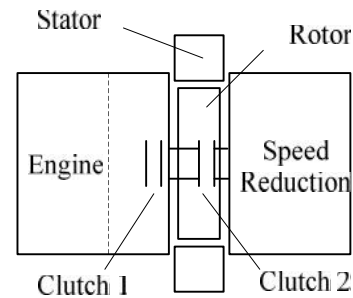


Figure 3. Hybrid power configuration in refitted HEV

3. Development Of High-Peep Fractional-Slot Concentrated-Winding BLDC

3.1 Proper electric machine technology used in the new hybrid power configuration

In common engine vehicle, as mentioned above, there is a small gap between the engine and the speed reduction which can be occupied by a specially developed electric machine in the refitted HEV with the new hybrid power configuration. Take a refitted HEV for example which needs an equipped electric machine with such structure restriction and performance requirements as follows:

- Rated power (kW): 3.5
- Rated voltage (Vdc): 96
- Rated speed (rpm): 2500
- Maximum axial length (mm): 70

In order to satisfy the above structure and rated specifications and other needed performance requirements such as high efficiency which are essential for EV and HEV, disc axial-flux permanent magnet brushless electric machine and fractional-slot concentrated-winding one should be alternative. The former should adopt wound core to reduce the iron loss especially when in relatively high spinning speed which leads to complicated fabrication and high cost, so the latter is chosen which is characterized as very short winding end. Fractional-slot concentrated-winding permanent magnet brushless electric machine are widely applied in low-speed direct-driven field and low-speed generator and always appears in sinusoidal current waveform [3] [4]. In this paper, 120° rectangular waveform of supply current is adopted for the developing fractional-slot concentrated-winding permanent magnet brushless electric machine and the electric machine is named as fractional-slot concentrated-winding BLDC whose intrinsically large torque ripple is not paramount for the high-speed application of this new hybrid power configuration.

3.2 Development of the fractional-slot concentrated-winding BLDC

3.2.1. Pole number

Large pole number of the BLDC will yield a small back-up yoke depth dimension, then a large rotor inner space which is good for occupation of clutch 2 of the new hybrid power configuration, but resulting in a large core loss especially when the machine reaches high

spinning speed of 2500 rpm. Through the trade-off comparison between the machine dimension and core loss, 10 pole number of the BLDC is chosen.

3.2.2. Stator slot number and winding configuration

Three-phase 10-pole BLDC, 12-slot with a double winding is a good choice which features a high fundamental winding factor of 0.933 and very small unilateral magnetic force.

3.2.3. Stack height

The BLDC can be equipped in the new hybrid power configuration with the elimination of two end covers which are replaced by output end cover of engine and input end cover of speed reduction respectively. In fact, in order to verify the BLDC performance off-line, the prototyped BLDC is fabricated with two end covers and the stack height is determined as 26mm, as a result, the rated requirements are satisfied by adjusting the stator outside diameter freely.

3.2.4. Core flux density

The core loss in BLDC is approximately proportional to 1.3 power of reversal frequency and square of effective (r.m.s.) value of flux density respectively in its stator teeth and back up. Considering the 10-pole BLDC with high rated speed of 2500 rpm which results in a high reversal frequency of flux density in the core, the effective value of core flux density should be relatively lower than the normal 50Hz electric machine in order to minimize the core loss. In fact, the target is easy to realize because of the larger circumference dimension of this BLDC approaching a large back up depth and teeth width and then a lower value of core flux density. In the original design, the flux density values of teeth and back up are determined approximately as 1.2 Tesla and 1.0 Tesla respectively when at no-load, then an optimal design is done to satisfy the rated specifications and other performance requirements such as efficiency. As any other types of electric machines, the BLDC enjoys a maximum efficiency when the copper loss equals to core loss, as a result, the BLDC must feature a lower core loss owing to its lower copper loss resulting from short winding end of fractional-slot concentrated-winding structure.

3.2.5. Rotor position sensor

Hall sensors are adopted to achieve the machine's rotor position owing to its small dimension and high reliability as opposed to any other position sensors, so three hall sensors are located in the teeth or slots to rule out the additional axial dimension. For three-phase BLDC, whether fractional-slot concentrated-winding structure or integer-winding one, three hall sensors should be located in the axis center position of magneto motive force for three windings with 120° electric angular degree different from each other. As a result, for three-phase 10pole/12slot double-winding BLDC, one sensor is first equipped in the slot open where two coils not belong to the same phase, then other two sensors are located in positions of 120°mechanical angular degree (the same as 120°electric angular degree) different from each other.

3.2.6. Permanent magnet

The magnet of NdFeB (neodymium iron boron) is chosen which features residual flux density of about 1.23 Tesla and coercive force of more than 1000 kA/m at 20°Celsius degree. Based on above issues of the BLDC, structure specifications of the prototyped BLDC are determined as shown in Table 1 and the cross section is depicted in Figure 4.

Two dimension (2D) finite element method (FEM) is adopted to verify the achieved performance requirements. With consideration of its structure characteristics of the very small length-to-diameter ratio, the three-dimension (3D) FEM is also and only used to calculate the no-load phase winding electromotive force (EMF) as a comparison with that from 2D-FEM as shown in Figure 5, and Figure 6 gives its 3D-FEM model and mesh grid respectively. It can be seen from Figure 5 that the 2D-FEM calculation shows a good coincidence with 3D-FEM one even in such a BLDC of small length-to-diameter ratio.

Table 1. Structure specifications of the prototyped BLDC

Parameter	Value
Outer diameter of stator	246 mm
Inner diameter of stator core	165 mm
Pole-arc coefficient of magnet	0.98
Outer diameter of magnet	160 mm
Inner diameter of magnet	151 mm
Inner diameter of rotor core	114 mm
Stack length	26 mm
Turn number per coil	12
Branch number	1
Wire gauge	6×1.12
Winding Configuration	Double winding
Tooth width (Parallel tooth)	30 mm

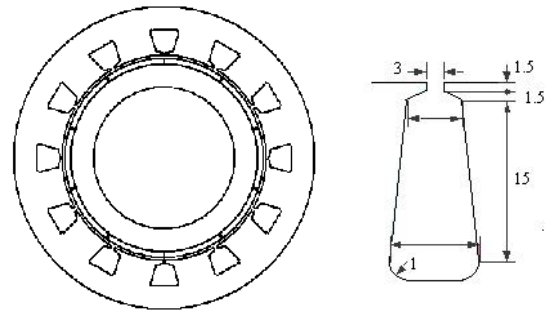


Figure 4. Cross section of the prototyped BLDC

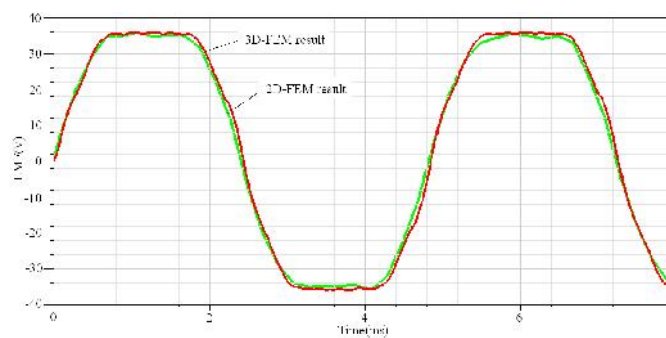
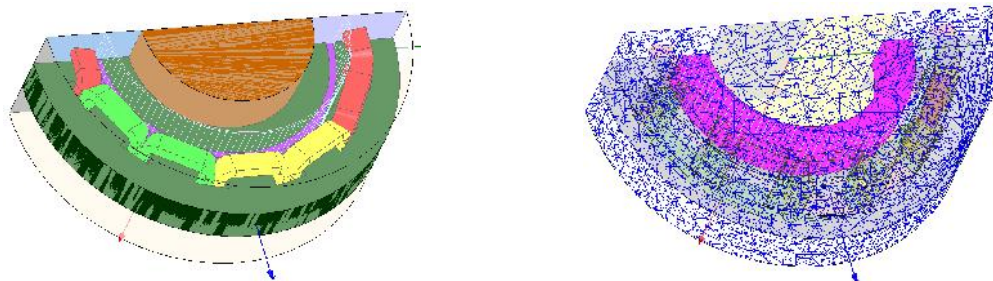


Figure 5. No-load EMF waveforms from 2D-FEM and 3D-FEM respectively

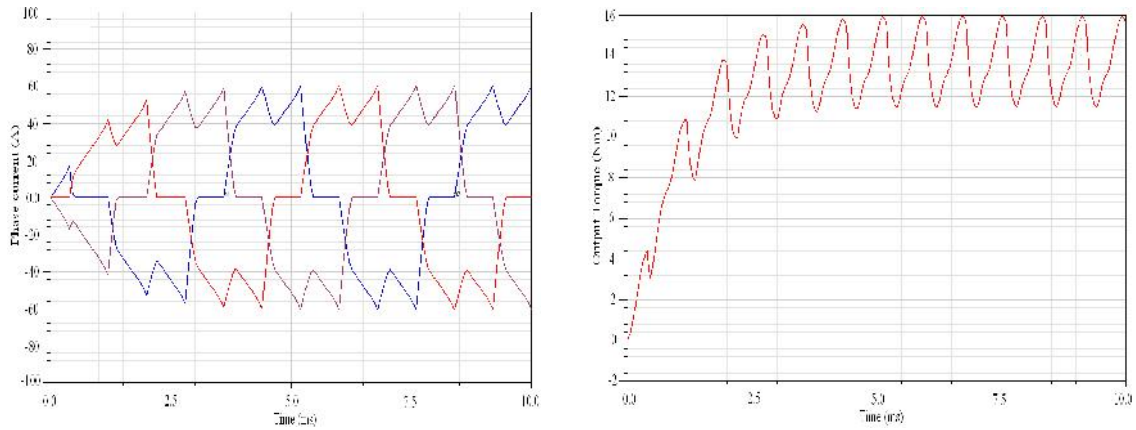


(a) 3D-FEM model

(b) Mesh grid

Figure 6. 3D-FEM model and its mesh grid

Designating the rated torque and rated speed, the transient waveforms of three phase currents and torque by 2D-FEM are achieved when simulated from standstill as shown in Figure 7. And the simulation efficiency at rated operation is about 84% which includes that of the electric machine and its inverter. From Figure 7(b) it is clear that there is much larger torque ripple which maybe not result in a very bad shortcoming since the BDCM is used in this new hybrid power configuration, but it is a good try to eliminate or reduce the torque ripple at a trade-off cost. A small additional slot with the same dimensions as that of the slot open of the BLDC located in the center line of the teeth is a good choice to diminish the slot torque ripple, one resource of the torque ripple, as shown in Figure 8. Figure 9 shows the big difference for weakening the slot torque ripple when the BLDC with or without the additional slots.



(a) Three phase current waveforms (b) Torque waveform
 Figure 7. Transient waveforms of phase current and torque from 2D-FEM

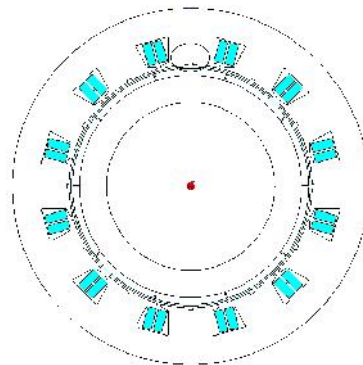


Figure 8. The BLDC with additional slots in the teeth center

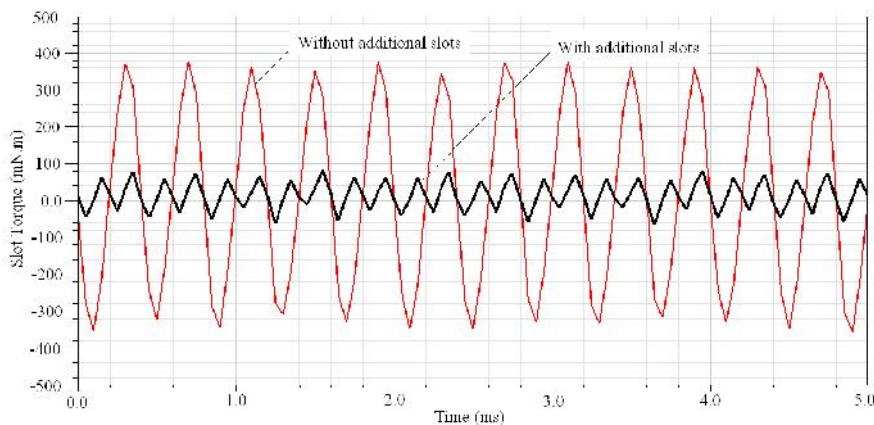


Figure 9. Slot torque ripple comparison when the BLDC with and without additional slots

4. Prototyped BLDC fabrication and experiment

Prototyped BLDC is fabricated as shown in Figure 10 with 70mm interval between two end covers and outer diameter of 260mm. Figure 11 gives the experiment setup. The experiment has been realized initiated from no-load then enlarging the load torque automatically and gradually while supplying no-load 96Vdc direct current voltage as the input to the inverter

that is to drive the motor and keeping the same 100% of duty-cycle ratio of pulse-width modulation (PWM). The experiment results are shown in Figure 12, where the spinning speed, dc bus voltage, dc bus current and efficiency as a function of output power are depicted and all the parameters except the outer power are described as their relative values. From Figure 12, it can be found that, the prototyped BLDC can spin at about 3500 rpm when at no-load and achieve an maximum efficiency of about 83% approximately happened in rated operation with the higher efficiency in the whole range of output power and speed. As a result, the prototyped BLDC satisfies performance requirements and dimensions demands of the refitted HEV equipped the new hybrid power configuration.



(a) The whole prototyped BLDC



(b) Stator of prototyped BLDC

Figure 10. The prototyped BLDC



Figure 11. The experiment setup

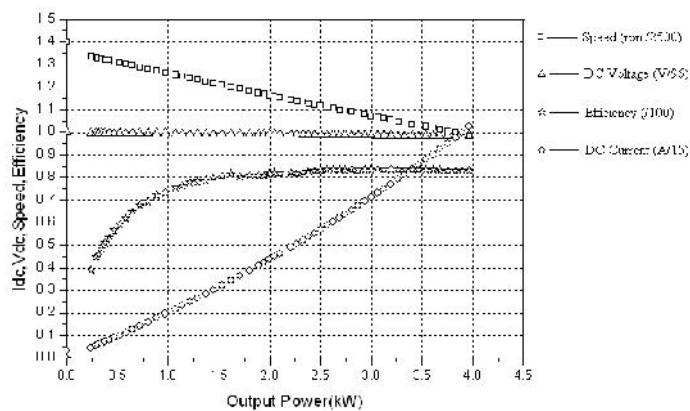


Figure 12. Load experiment results as the function of the output power

4. Conclusion

1. A new type of hybrid power configuration which can be used in HEV is presented with different control strategies and EV performance based on different weight of fuel power and battery power.
2. In order to realize the new power configuration especially in refitted HEV, fractional-slot concentrated-winding BLDC with high spinning speed and very small length-to-diameter ratio structure is presented.
3. The prototyped BLDC with rated specifications of 96Vdc, 2500r/min and 3.5kW and with 70mm interval between two end covers and stator outer diameter of 260mm is developed and fabricated to realize refitted HEV equipped with the new hybrid power configuration. It is shown from the experiment results that the prototyped BLDC not only satisfies performance requirements but the structure limitation for the refitted HEV.

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