A New On-board Charging-Driving Integrated Topology for V2G Technology

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Abstract: The performance of batteries and on-board chargers (such as the volume in the car, energy storage capacity and charging speed) needs to be improved, which has become one of the main factors restricting the development of electric vehicles. The development of Vehicles to Grid technology puts forward higher requirements for chargers. With the development of Vehicles to Grid (V2G) technology, more realizable functions put forward higher requirements for chargers. To solve the problem of charging system in electric vehicle, a charging-driving integrated topology was designed, which makes full use of two-stator motor and inverters to be transformed to a charging system. The supercapacitor and the battery are used to form the hybrid power system. In the driving mode, the startup and acceleration performance of the vehicle are improved. In the charging mode, the various functions of Vehicles to Grid technology can be satisfied, and the electrical isolation is realized. This topology not only improves the power, but also greatly reduces the charging/discharging times of the battery, and improves the overall performance of the system. The feasibility is verified by simulation.

Keywords: EVs; supercapacitor; battery; charger; V2G

1. Introduction

1.1. Background

The core technologies of new energy vehicles are motor, battery and electronic control. At the present stage, the technological development of batteries has not yet met the technical requirements of electric vehicles (EVs), and the performance in terms of range capacity, power density, continuous charge and discharge is not ideal.

The existing on-board charging system generally has problems such as high cost, large volume, large weight, low power level, non-negligible harmonic pollution to the power grid and insufficient charging safety in rain and snow weather, etc., which hinder the popularization and promotion of electric vehicles [1–3]. Moreover, in the case of EVs driving in cities, frequent switching of the acceleration process and the braking feedback process leads to rapid and repeated charging and discharging of the battery, which will greatly shorten the service life of the battery. In addition, with the further development of Vehicles to Grid (V2G) technology, it is not only applied to orderly charge and discharge, but also applied to primary frequency regulation, spinning reserve, absorbing new energy and other aspects, so as to deepen the connection of vehicle network and realize more functions [4–7]. Different from the slow conversion of orderly charge and discharge, functions such as primary frequency modulation need to be adjusted quickly at any time according to the grid condition, so the battery will be repeatedly charged and discharged rapidly, causing great damage to the battery. Therefore, it is necessary to improve the structure of the traditional electric vehicle electric drive system, improve their dynamic performance, realize various V2G technologies and give full play to the role of electric systems.
vehicles as energy storage devices under the premise of supporting the normal operation of electric vehicles.

1.2. Current State of Integrated Topology

With the deepening of research, foreign researchers have proposed different types of topologies to realize the functions of on-board charging systems, and have conducted some research on the integrated hybrid topologies of driving and charging [8].

The existing integrated hybrid topology generally has two methods. The first method is to integrate the existing charging and driving topologies and reuse their switching tubes, components or windings of the motor. For example, ref. [9] adopted the idea of using motor winding as filtering inductance of charging circuit, and proposed a kind of integrated hybrid topology suitable for four-motor driven electric vehicles. Ref. [10] adopts single-phase charging system, and the motor windings are used as three parallel inductors, so the current passing through the motor is single-phase, there is no torque in the motor and it remains static. In [11], the winding inductance of the embedded permanent magnet synchronous motor (IPM) is used as the filter inductor, and the bidirectional DC/DC converter is connected to the DC side, which can convert the DC voltage to the required voltage level and charge the battery flexibly. This method is simple in principle and design, but low in coupling.

In the second method, on the basis of the first method, the structure of the motor is further improved to make it play a greater role in the charging process. For example, in [12], synchronous induction motor, three-phase H-bridge, capacitor and battery are used to constitute the charging circuit, which has an isolation function. [13] uses a synchronous reluctance motor of adding one more winding in the stator as a fixed air-gap transformer, so as to realize the integrated function of motor driving and charging. This method changes the motor structure and increases the complexity and cost of the motor winding and control method. The principle and design of this method are complicated, and there are many problems to be considered, but the coupling degree is high.

It can be seen that the research of charging-driving integrated topology of the EV is still in the initial stage. The optimization of the integrated topology, the utilization of motor windings, the choice of control strategy and many other basic and key problems are worthy of further study. When the motor winding is used as filter inductance in the charging circuit, how to solve the rotation problem of the motor rotor, avoid the magnetization of drive motor, eliminate or utilize the electromagnetic coupling between stator winding and rotor, and the inductance coupling between stator windings, how to realize the refactored converter with high power factor and low harmonic distortion, and whether the electrical isolation can be realized to protect the storage battery are the problems that need to be considered and studied.

1.3. Research Contents

In this paper, a novel charge-drive integrated topology based on Plug-in Hybrid Electric Vehicle (PHEV) is proposed which uses radial axial two-stator motor as drive hybrid excitation permanent magnet synchronous motor (two-stator HEPMSM) and uses supercapacitor and lithium battery to form a hybrid power system. It makes full use of the motor windings and builds a new topology with high power and high power factor correction, safety isolation, and realize the functions of V2G technology. It greatly reduces the charging/discharging times of the battery in the process of vehicle driving and V2G mode, and improves the overall service life and performance.

2. Power Circuit

The power circuit of the driving and charging topology is shown in Figure 1. The proposed topology is composed of a battery bank, a supercapacitor, a filter capacitor, 12 power MOSFET, and a two-stator hybrid excitation permanent magnet synchronous
motor (two-stator HEPMSM). The topology can realize the conversion between charging mode and driving mode by turning on and off the transfer switches and the SPST switch.

The two-stator HEPMSM used in this paper has two stators, one of which is located in the axial direction of the motor. In the radial direction, the structure of the motor is the same as that of the traditional inferior permanent magnet synchronous motor (IPMSM). The magnetic flux of the permanent magnet passes through the radial stator to form the radial main magnetic flux. In the axial direction, the magnetic pole on one side of the rotor is protruded into a fan ring block [14–16]. The axial stator and rotor were concentric to form a closed magnetic flux loop, forming the axial main magnetic flux. By adjusting the radial main flux and axial main flux, the motor can realize the transition between the magnetic-increased operation state and the magnetic-weak high-speed operation state. The motor has the advantages of IPMSM, such as compact structure, high air gap magnetic density, high torque density, and being easy to rotate at high speed. Moreover, compared to traditional inferior permanent magnet synchronous motor (IPMSM), the two stator HEPMSM has the following advantages: (1). The axial stator of the motor makes full use of the flux leakage at the motor end, improves the utilization of permanent magnet, the magnetic field distribution of the motor, and the torque density and power density of the motor; (2). The decoupling of magnetic weakening control and torque control is successfully realized. The two stators can use flux-weakening control separately or achieve torque output separately, the control mode is flexible; (3). The two stators of the motor can output torque independently, the motor has strong fault tolerance; (4). The optimal combination is obtained by adjusting the structural parameters of the two stators and the magnetic pole parameters of the rotor, so it can obtain a high sinusoidal back emf waveform and reduce the cogging torque without the use of chute and oblique pole. It is suitable for use in driving motors of electric vehicles for its good performance of torque output and speed regulation.

Then, the state space equation is used to deduce and establish the model of two-stator HEPMSM. Combined with the Classic PMSM mathematical model and the two-stator motor structure, the voltage equations in the dq0 reference frame can be written as below

\[ v_{d1} = r_s i_{d1} + \frac{d}{dt} \psi_{d1} - \omega_r \psi_{q1} \]  

\[ v_{q1} = r_s i_{q1} + \frac{d}{dt} \psi_{q1} + \omega_r \psi_{d1} \]
\[ v_{d2} = r_s i_{d2} + \frac{d}{dt} \psi_{d2} - \omega_r \psi_{q2} \]
\[ v_{q2} = r_s i_{q2} + \frac{d}{dt} \psi_{q2} + \omega_r \psi_{d2} \]  

For the same situation, the flux equations in dq0 reference frame can be written as below:
\[ \psi_{d1} = L_d i_{d1} + L_m d i_{d2} + \psi_{pm} \]  
\[ \psi_{q1} = L_q i_{q1} + L_m q i_{q2} \]  
\[ \psi_{d2} = L_m d i_{d1} + L_q d i_{d2} + \psi_{pm} \]  
\[ \psi_{q2} = L_m q i_{q1} + L_q q i_{q2} \]

where \( r_s, L_d, L_q, L_m, \) and \( L_{mq} \) are direct and quadrature winding resistance, self and mutual inductances, respectively. Moreover, \( L_d = L_1 + L_m d \) and \( L_q = L_1 + L_m q \). Additionally, \( v_{d1}, v_{d2}, v_{q1}, v_{q2}, i_{d1}, i_{d2}, i_{q1}, i_{q2}, \) \( \psi_{d1}, \psi_{d2}, \psi_{q1}, \psi_{q2} \) are direct and quadrature voltage, current and flux of axial and radial stator, respectively. \( \omega_r \) is electrical angular velocity.

From Equations (1)–(8) and motor motion equation, the state space equation of the two-stator HEFMSM can be obtained as follows.
\[ \frac{d i_{d1}}{dt} = \frac{1}{L_d^2 - L_{md}^2} \left[ L_d u_{d1} - L_m d s i_{d1} - L_m d u_{d2} + (\omega L_q L_d - \omega L_m q L_{md}) i_{q1} + (\omega L_m q L_d - \omega L_q L_m d) i_{q2} \right] \]  
\[ \frac{d i_{d2}}{dt} = \frac{1}{L_d^2 - L_{md}^2} \left[ L_d u_{d2} - L_m d s i_{d2} - L_m d u_{d1} + L_m d s i_{d1} + (\omega L_q L_d - \omega L_m q L_{md}) i_{q2} + (\omega L_m q L_d - \omega L_q L_m d) i_{q1} \right] \]  
\[ \frac{d i_{q1}}{dt} = \frac{1}{L_q^2 - L_{mq}^2} \left[ L_q u_{q1} - L_q R i_{q1} - L_m q u_{q2} + L_m q R i_{q2} - (\omega L_d L_q - \omega L_m d L_{mq}) i_{d1} - (\omega L_m d L_q - \omega L_d L_{mq}) i_{d2} - \left( \omega L_q \psi_{pm} - \omega L_m q \psi_{pm} \right) \right] \]  
\[ \frac{d i_{q2}}{dt} = \frac{1}{L_q^2 - L_{mq}^2} \left[ L_q u_{q2} - L_q R i_{q2} - L_m q u_{q1} + L_m q R i_{q1} - (\omega L_d L_q - \omega L_m d L_{mq}) i_{d2} - (\omega L_m d L_q - \omega L_d L_{mq}) i_{d1} - \left( \omega L_q \psi_{pm} - \omega L_m q \psi_{pm} \right) \right] \]  
\[ \frac{d \omega}{dt} = \frac{P_n}{J} (T_e - T_L) \]

where \( \omega, T_e, T_L, J, P_n \) are the electric angular velocity, electromagnetic torque, load torque, moment of inertia, pairs of magnetic poles of the drive motor, respectively.

In this topology, supercapacitors and lithium-ion batteries are used to form the power supply system of electric vehicle.

Supercapacitors, also known as double-layer capacitors or electrochemical capacitors, are a new electrochemical energy storage element between electrostatic capacitors and batteries, and are considered to be a very promising energy storage element in the 21st century. As a new type of energy storage device, it has unique advantages in the application of pulsating loads due to its high power density, excellent charge-discharge performance, long cycle life and other advantages. However, from the current product, the specific energy of supercapacitor is lower than that of battery, which is about 20% of battery. So it is not suitable to be used as a large-scale electric energy storage device alone. If supercapacitor and battery are combined to form a composite power supply, the combination of high specific energy of battery and high specific power of supercapacitor will undoubtedly bring significant performance improvement to the electric energy storage device. Table 1 shows the performance parameters of supercapacitors and lithium-ion batteries.

In this paper, the lithium-ion battery and supercapacitor are combined in different ways through turn-off and turn-on of the transfer switches and the SPST switch, so as to achieve different functions in the driving mode and charging mode.
Table 1. Comparison of Performance Parameters between Supercapacitor and Lithium-ion battery [17–20].

| Parameters                     | Unit  | Supercapacitors | Lithium-Ion Batteries |
|-------------------------------|-------|-----------------|-----------------------|
| Single Nominal Voltage        | V     | 2.7~2.85        | 3.7                   |
| Working Temperature           | °C    | −20~+70         | −20~+60               |
| Charging Cycle Times          | thousand times | 100~1000       | 0.5~10                |
| Electric Capacity             | F     | 100~12,000      | -                     |
| Specific Energy               | mWh/g | 4~9             | 100~265               |
| Specific Power                | W/g   | 3~10            | 0.3~1.5               |
| Efficiency                    | %     | 95              | 90                    |
| Working life                  | years | 5~10            | 3~5                   |
| Low Temperature Capacity Decay| % (−20 °C PS25 °C) | 30              | 3~5                   |
| Energy Cost                   | RMB/kWh | 2500          | 10,000                |
| Power Cost                    | RMB/kW  | 6000          | 650                   |

2.1. Driving Mode

For driving mode, the transfer switches are at position 1 and the SPST switch is on. As shown in Figure 2, the hybrid power system in the driving mode consists of the battery connected directly in parallel with the supercapacitor through an inductor. The function of the inductor is to filter the output current of the battery and reduce the current ripple, so as to reduce the internal heat and energy loss. This kind of connection has the advantages of simple structure, simple control and high reliability, which can improve the power output ability of the system and optimize the discharge process of the battery.

The battery power can be converted to desired voltage and frequency by three-phase PWM inverters, and supplied to the axial and radial stators of the traction motor. The two-stator motor used in this paper consists of a spoke-type rotor, a radial stator, and an axial stator. The axial stator is placed on the side of the radial stator, and both stators contain conventional ac three-phase windings. The motor has high power density, excellent flux regulation performance, wide speed range, suitable for use as an electric vehicle drive motor.

Compared with the battery of the same capacity, the hybrid power system has greater power output and better performance of large current discharge. When the car starts up or accelerates, the supercapacitor discharges instantaneously to provide instantaneous power, and then the battery will gradually increase the current under the influence of inductance to provide a stable power output. When the car is regenerative braking or slowing down, the supercapacitor quickly absorbs energy, as does, subsequently, the battery through the inductor. Therefore, the starting and accelerating performance of EVs has been improved and the service life of the battery has been extended after using hybrid power system.

2.2. Charging Mode

For charging mode, the transfer switches are at position 2 and the SPST switch is off. The equivalent circuit diagram is shown in Figure 3 above. The radial windings of the motor are connected to the AC grid, which makes the rotor of the motor rotate at a synchronous speed and generates an induced electromotive force on the axial windings. Therefore, it can replace the transformer to realize the electrical isolation of charging. The loss of the electrical isolation part is determined by the loss when the motor is running.

The following will analyze the feasibility of the double-stator hybrid excitation motor used in the first level topology from the perspective of motor mathematical model.
Figure 2. Diagram of driving mode.

Combined with the Classic PMSM mathematical model and the two-stator motor structure according to the Equations (1)–(8), the voltage equations in dq0 reference frame can be written as below after some mathematical manipulations.

\[
v_{d2} = r_s(i_{d2} - i_{d1}) + L_i \frac{d}{dt}(i_{d2} - i_{d1}) - \omega_r L_i (i_{d2} - i_{d1}) + v_{d1}, \tag{14}
\]

\[
v_{q2} = r_s(i_{q2} - i_{q1}) + L_i \frac{d}{dt}(i_{q2} - i_{q1}) + \omega_r L_i (i_{q2} - i_{q1}) + v_{q1}, \tag{15}
\]

The equations above are similar to equations in dq0 the reference frame that describe the classical three-phase PWM rectifier. So the AC section in Figure 3 can be equivalent to a three-phase PWM rectifier. The control of the AC section can use three-phase PWM control to realize high power, and low harmonic content.

In the DC/DC section, the battery and the supercapacitor are connected to the AC/DC section via two bi-directional buck converters. This structure has higher flexibility and wide voltage control range, and can quickly adjust the output voltage of the battery, so that the battery can continue to charge and discharge within the appropriate working range. It can also effectively adjust the output voltage of the supercapacitor, giving full play to the supercapacitor’s characteristics of the large current charge and discharge. During the charging process, the supercapacitor and battery can be adjusted independently or cooperate with each other to realize different functions of V2G.
2.3. V2G Functions

One of the main functions of V2G is to realize the orderly charge/discharge control of EVs by setting the constraint conditions, so as to relieve the load pressure of the grid. In the orderly charge/discharge control, the power system of EVs should charge or discharge continuously in a specified period according to the demand of the grid. The switch of charging/discharging is not frequent, and sufficient capacity is required for long periods of charging/discharging time. The batteries have higher specific energy and can be charged or discharged continuously for a long time. So the function of orderly charging and discharging is realized by the battery according to the above requirements and the working characteristics of the battery section.

Frequency regulation of the micro-grid is one of the important functions of V2G. In frequency regulation, the EV’s power system should adjust the amplitude and direction of its active power according to the load change of the micro-grid, so as to maintain the load balance. The switch of charging-discharging is frequent and rapid, and sufficient power is required. Compared with batteries, supercapacitors have higher specific power, energy utilization rate and longer cycle life. Therefore, the function of frequency regulation is realized by the supercapacitor according to the above requirements and the working characteristics of the supercapacitor section. The same is spinning reserve, absorbing new energy.

3. Results and Discussion

3.1. Driving Mode

This paper uses Simulink to verify the feasibility of the topology. Model parameters of two-stator HEPMSM are shown in Table 2. The model of two-stator HEPMSM can be established by state space equation according to the Equations (9)–(13).

| Parameters | J     | $L_{md}$ | $L_{mq}$ | $L_d$ | $L_q$ | R  | $P_n$ |
|------------|-------|----------|----------|-------|-------|----|-------|
| Unit       | Kg $\times$ m$^2$ | mH       | mH       | mH   | mH       | $\Omega$ | $-$   |
| Value      | $1.437 \times 10^{-5}$ | $-0.48$  | $-0.089$ | $7.11$ | $10.55$ | $0.9$ | $4$   |

In this paper, Dual dq axis control strategy is adopted to drive the two-stator HEPMSM in the drive mode. The simulation model is shown in the Figure 4 below. The total simulation duration is 1 s, and the motor starts at 0 s. At this time, the given speed is 1000 r/min. After 0.2 s, the given speed rises to 1400 r/min. After 0.4 s, the given speed drops to 800 r/min. At 0.6 s, the load torque changes from no-load to 0.2 N $\times$ m.
Through simulation, the speed waveform and torque waveform of the two-stator HEPMSM are obtained as shown in the Figures 5 and 6.

In Figure 5, there is minor discrepancy between the given speed and measure speed, because the rotor of the motor has a certain inertia, causing the measured speed impossible to change suddenly with the given speed. It takes 0.008 s for the two-stator HEPMSM to reach the specified speed from starting up. When the given speed is transformed, the motor takes 0.005 s to reach the new given speed. In Figure 6, When the load torque of the motor changes to 0.2 N × m, it takes 0.005 s for the motor to return to steady state again.

It can be seen that the two-stator HEPMSM has good steady-state performance and dynamic following performance in the driving mode.
3.2. Charging Mode

PWM rectifier with electrical isolation composed of two-stator HEPMSM is simulated by Simulink. The simulation model of charging mode was established. The circuit of the AC/DC section adopts voltage and current double closed-loop control, and the control model is shown in the Figure 7.

Figure 8 shows the current waveform of the two stators after starting the charging circuit. It can be seen that the circuit enters the steady state 0.45 s after the beginning of simulation. According to Table 1, the voltage and current of the axial stator on the secondary side is in a fixed proportion to the voltage and current of the radial stator on the primary side at the steady state. It can be obtained from Table 3 that the power loss from primary side to secondary side is very small, the power transmission efficiency is 91.38%. The results show that two-stator HEPMSM can replace the transformer to realize electrical isolation.
Figure 8. (a) Waveform of radial stator current; (b) Waveform of axial stator current.

Table 3. RMS Voltage (V) and Current (A) value and Power (W) of two-stator motor’s winding (steady-state).

|       | Voltage A | Voltage B | Voltage C | Current A | Current B | Current C | Power   |
|-------|-----------|-----------|-----------|-----------|-----------|-----------|---------|
| Radial| 67.53     | 67.30     | 67.43     | 2.046     | 2.065     | 2.068     | 416.57  |
| Axial | 66.46     | 66.23     | 66.48     | 1.917     | 1.917     | 1.917     | 380.68  |

4. Conclusions

An on-board integral topology was developed, which can run in charging mode or driving mode by closing or opening several switches. The two-stator motor and two inverters, which are used for the traction of EV, can be transformed to the charger. It realizes the electrical isolation without transformers, which reduces the size and cost of the topology. In the drive mode, the supercapacitor and the battery are directly connected in parallel, the car has better start-up and acceleration performance and longer battery life. In the charging mode, the supercapacitor and battery are separated through the DCDC converter, which avoids the problem of high self-discharge rate in direct parallel connection, and can realize the different functions of V2G technology, respectively, under the condition of minimizing the damage to the battery. High power and high power factor can be achieved when charging. The simulation results show that the two-stator HEPMSM has good performance in the driving mode and also verify the feasibility of using the two-stator HEPMSM to reconstitute the three-phase PWM rectifier circuit with electrical isolation.

5. Future Research Directions

The above simulation results verify the feasibility of this topology, and future research directions are below.

1. Design the control strategy to make the battery and the supercapacitor work together and complete different V2G functions;
2. Design the corresponding regenerative energy braking strategy according to the characteristics of the topology structure, improve driving range and energy efficiency;
3. Built the experimental platform to verify its performance, analyze vibration and noise of the topology operating in drive mode and charge mode.
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