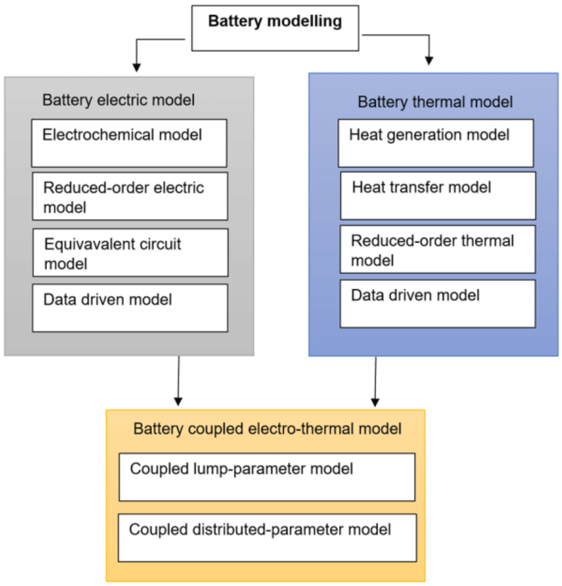
12) Battery models can be classified into three main types: electric, thermal, and coupled models (other models, such as kinetic models, are used less in BMS design). The three classifications of battery modelling are presented in diagram.



Battery Electric Model

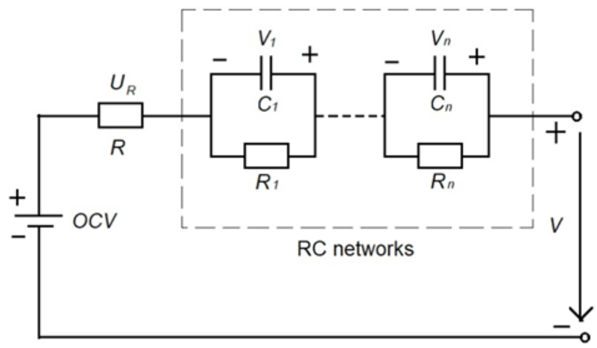
The battery-electric model includes the electrochemical model, reduced-order model, equivalent circuit model, and the data-driven model.

The electrochemical model provides information about battery electrochemical behaviors. This model can be very accurate but requires a complex simulation and computation effort. Because of this, it is difficult to implement this model in a real-time application.

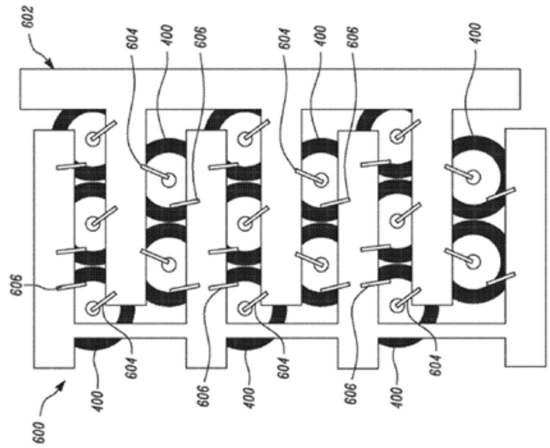
Consequently, **the reduced-order electric model** is developed as a simplified physics-based electrochemical model to estimate Li-ion battery state of charge (SoC). Simplified reduced-order electric models provide less information, but are still convenient for real-time battery applications.

The equivalent circuit model is the most commonly used battery model in a BMS. This model estimates battery-electric behaviors based on the battery equivalent circuit which contains a combination of circuit components, such as resistors, capacitors, and voltage sources. This model has been widely adopted in real-time battery applications mostly because of its simple structure and small number of parameters.

The typical battery equivalent circuit is shown in Figure 1. The resistor-capacitor networks simulate transient responses of the battery during charging and discharging transients. The number of R-C networks represents the model order, which has to be carefully determined. In real applications, the first and second-order models are usually used. The R-C network models have a better dynamic performance for SoC and power predictions.



Regulating battery temperature is an important task of the BMS. A battery's performance can decrease if operated in higher or lower temperatures. Different cooling systems are usually used to maintain proper battery temperature. For example, Tesla uses a patented battery pack design with a plate-based cooling system to dissipate the heat and regulate battery temperature.



In order to capture accurate battery thermal behaviors, the battery thermal model contains different models such as heat generation, heat transfer, reduced-order thermal, and data-driven models. The heat generation is described by three equations:

$Q1=R\cdot I2$

$Q2=I\cdot V\text{-}OCV$

$Q3=I\cdot(V\text{-}OCV)+ITdOCVdT$

where R is battery internal resistance, I is battery current, V is battery voltage, and OCV is battery open-circuit voltage. Heat marked with Q1 represents the battery heat caused by the large current crossing the battery internal resistance. Q2 is the battery heat open-circuit by the over-potentials across the R-C network. Finally, Q3 is the battery heat generation caused by both the entropy change and Joule heating.

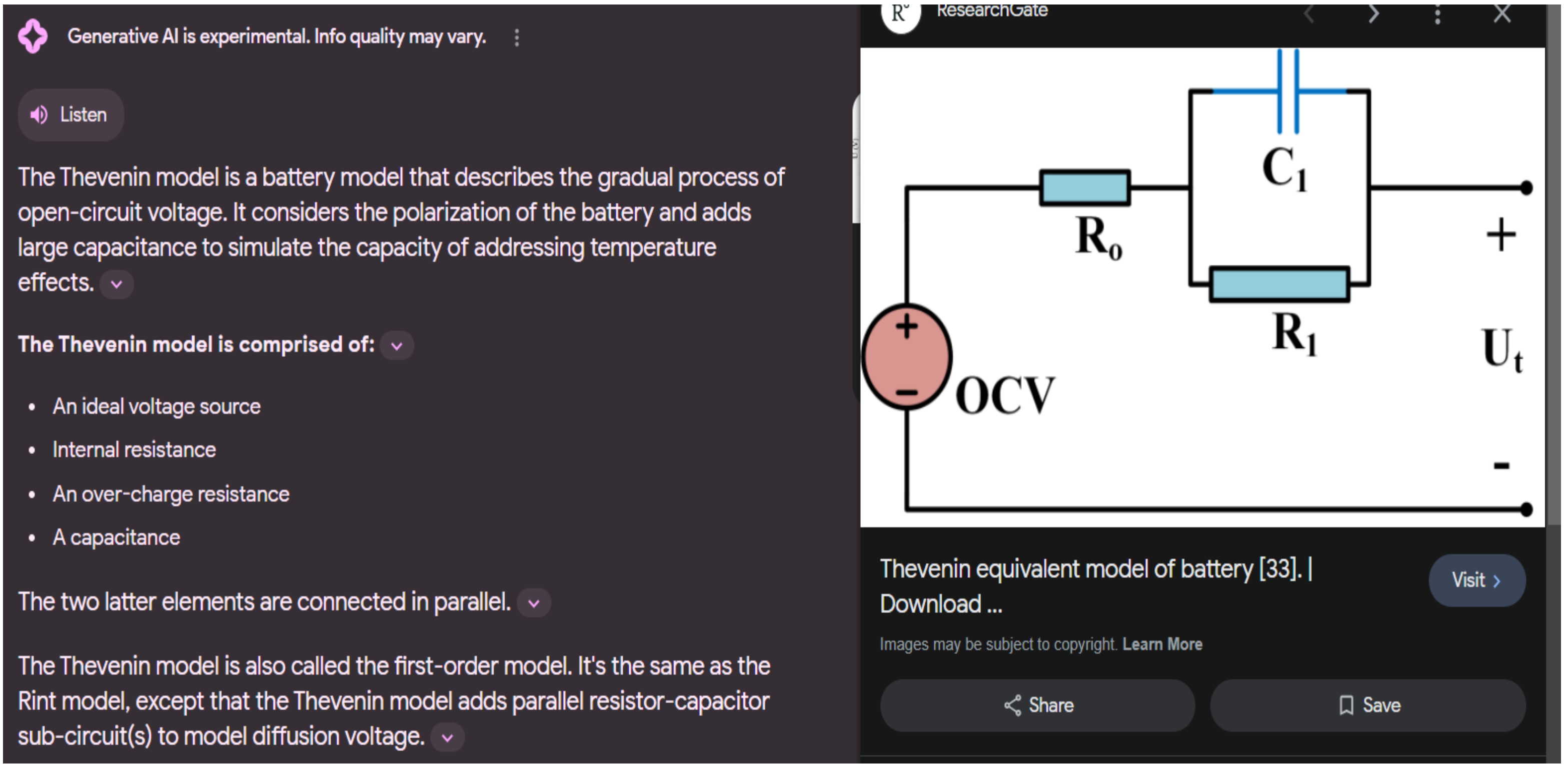
The three main forms of the battery **heat transfer model** are heat convection, heat conduction, and heat radiation. For the Li-ion battery, a 3D distributed-parameter heat transfer model is developed that analyzes the distribution of the geometrical current and heat inside the battery. The 3D heat transfer models calculate temperature distribution inside the battery, which is important for applications that require high heating of the battery. The model can be used to detect possible temperature hot spots inside the battery. One dimensional heat transfer model calculates the temperature gradient along one direction. These models require too large computational overheads which are not convenient for real-time applications, so they are mainly used in offline simulations.

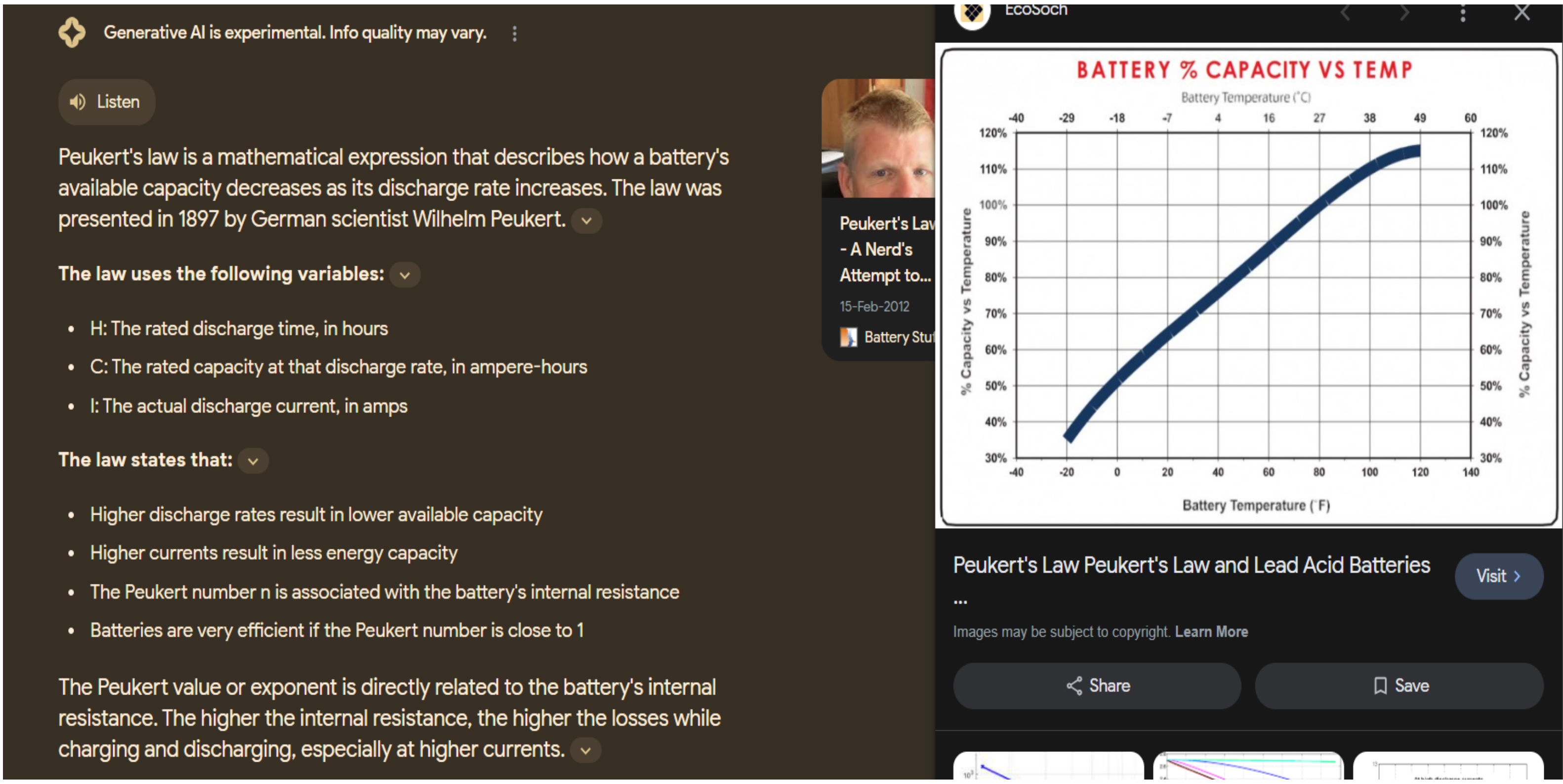
The reduced-order thermal model needs to provide the control purpose for battery thermal management. This model reduces the order of a Li-ion battery model by converting the one-dimensional boundary-value problem into a low-order linear model in the frequency domain.

Battery Coupled Electro-Thermal Model

The battery coupled electro-thermal model captures the battery's electric (current, voltage, SoC) and thermal (surface and internal temperature) behaviors simultaneously. Several coupled electro-thermal models have already been developed. A 3D electro-thermal model estimates battery SoC and calculates heat generation and distribution under both constant and dynamic currents. This model contains a 2D potential distribution model and a 3D temperature distribution model.

A reduced low-temperature electro-thermal model has been validated by batteries with three cathode materials. This model is accurate for developing fast heating and optimal charging approaches under low-temperature conditions.
The 3D electro-thermal model is used to analyze the influences of different battery operation conditions on the battery temperature, such as coolant flow-rate and discharge current. Based on the analysis of this model, the contact resistance also plays an important role in the battery temperature.





6) There are various methods of charging lead acid batteries, but the most common are:

Constant voltage charging: This method applies a constant voltage to the battery until it is fully charged. The charging current decreases as the battery voltage increases. Constant voltage charging is the most common method for charging sealed lead acid (SLA) batteries.

Constant current charging: This method applies a constant current to the battery until it is fully charged. The battery voltage increases as the battery charges. Constant current charging is the most common method for charging flooded lead acid batteries.

Taper current charging: This method applies a high charging current at the beginning of the charge cycle, which is gradually reduced as the battery charges. Taper current charging is not as common as constant voltage or constant current charging, but it can be used to charge both SLA and flooded lead acid batteries.

Two-step constant voltage charging: This method uses two different constant voltages to charge the battery. The first voltage is higher and is used to quickly charge the battery to about 70% of its capacity. The second voltage is lower and is used to finish charging the battery and prevent overcharging. Two-step constant voltage charging is often used to charge large lead acid batteries, such as those used in electric vehicles and solar power systems.

The best charging method for a lead acid battery depends on the type of battery and its intended application. For example, SLA batteries are typically charged using constant voltage charging, while flooded lead acid batteries are typically charged using constant current charging.

In addition to the charging method, there are a number of other factors that can affect the charging of lead acid batteries, such as the temperature, the age of the battery, and the state of charge of the battery. It is important to follow the manufacturer's instructions when charging lead acid batteries to avoid overcharging, which can damage the battery and shorten its lifespan.

Here are some additional tips for charging lead acid batteries:

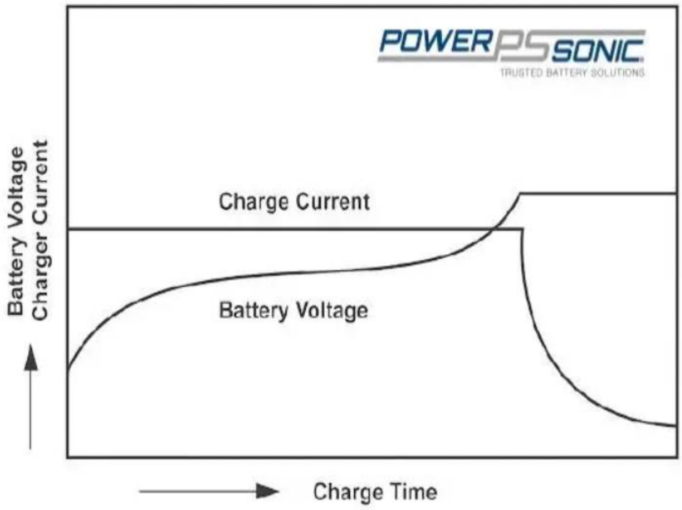
Charge the battery in a well-ventilated area.

Do not overcharge the battery.

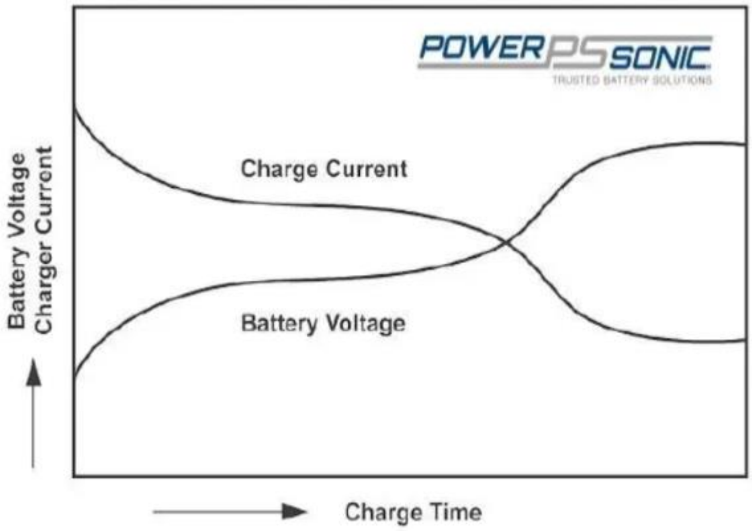
If the battery is going to be stored for an extended period of time, charge it to about 50% of its capacity and store it in a cool, dry place.

If the battery becomes sulfated, it can be desulfated using a special charger or battery desulfator.

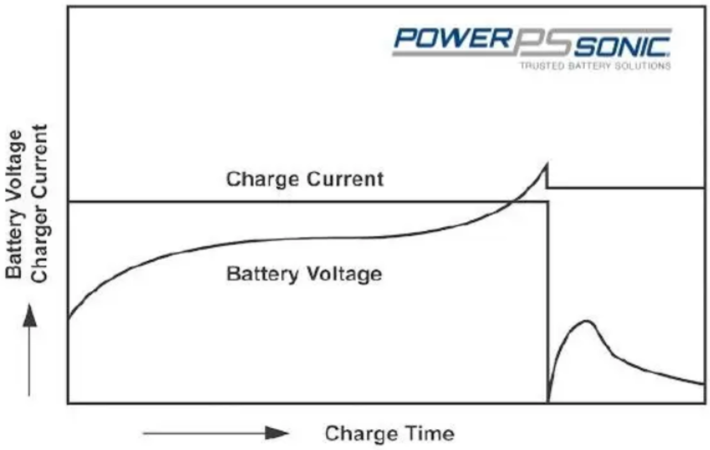
7)



Constant voltage charging characteristics



Taper current charging characteristics for this type of basically unregulated charger



Two-step constant voltage charging characteristics.

5)

2. The Principle of the PMSM

The operation of a PMSM is similar to a three-phase induction motor. The three-phase voltage source connected with the stator winding produces a rotating magnetic field (RMF). The RMF cause the rotor to turn. The power losses in the rotor side do not occur because the rotor of PMSM is a permanent magnet. Moreover, this machine can provide a constant torque. The structure and equivalent circuit of the PMSM are shown in Fig. 1.

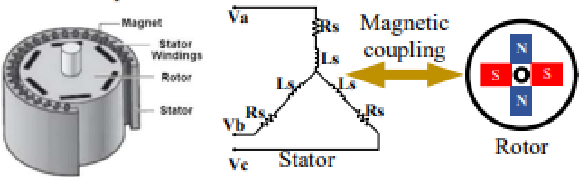


Fig. 1 The structure and equivalent circuit of the PMSM

3. Mathematical Model of the PMSM

The DQ modeling method is applied to derive a mathematical model of the system as depicted in Fig. 2. The DQ–axis in Fig. 3 is rotated with the angular speed (ω_r) by phase shift (θ_r). The stator voltages (v_{abc}) can be written for three-phase system as follows:

$$v_{abc} = R_s i_{abc} + \frac{d}{dt}(L_s i_{abc} + \lambda_{pm}(\theta)) \quad (1)$$

$$\frac{d}{dt}\lambda_{pm}(\theta) = -\omega_r \lambda_{pm} \begin{bmatrix} \sin(\theta_r) \\ \sin(\theta_r - 2\pi/3) \\ \sin(\theta_r + 2\pi/3) \end{bmatrix} \quad (2)$$

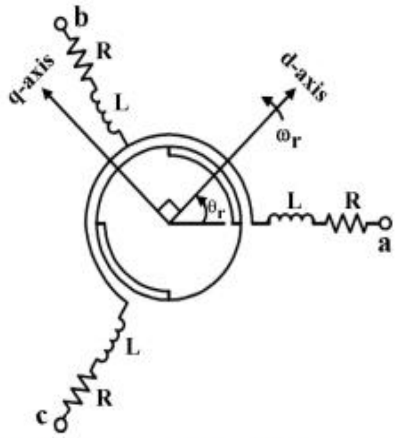


Fig. 3 The vector diagram for DQ transformation

$$\left.\begin{aligned} v_a &= R_s i_a + L_s \frac{d}{dt} i_a - \omega_r \lambda_{pm} \sin(\theta_r) \\ v_b &= R_s i_b + L_s \frac{d}{dt} i_b - \omega_r \lambda_{pm} \sin(\theta_r - 2\pi/3) \\ v_c &= R_s i_c + L_s \frac{d}{dt} i_c - \omega_r \lambda_{pm} \sin(\theta_r + 2\pi/3) \end{aligned}\right\} \quad (3)$$

where the $\frac{d}{dt}\lambda_{pm}(\theta)$ in (2) is the back EMF. Then, the mathematical model on three-phase system in (3) can be transformed into the DQ-axis. The dynamic equation of the PMSM on DQ-axis can be written in (4) - (5).

$$v_d = R_s i_d - \omega_r \lambda_q + \frac{d}{dt}\lambda_d = R_s i_d + L_d \frac{d}{dt} i_d - \omega_r L_q i_q + \frac{d}{dt}\lambda_{pm} \quad (4)$$

$$v_q = R_s i_q + \omega_r \lambda_d + \frac{d}{dt}\lambda_q = R_s i_q + L_q \frac{d}{dt} i_q + \omega_r L_d i_d + \omega_r \lambda_{pm} \quad (5)$$

As a result, the equivalent circuit of the PMSM in DQ-axis derived by using DQ modeling method is shown in Fig. 4.

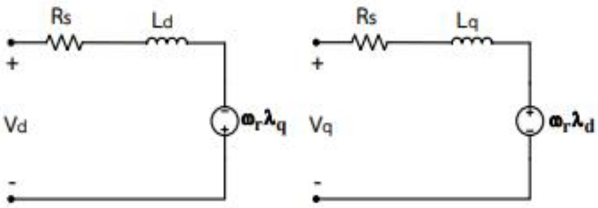
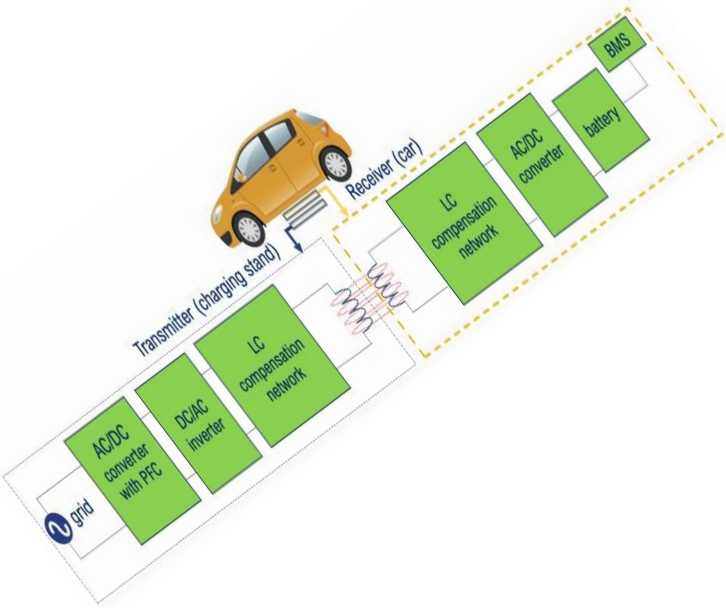


Fig. 4 The PMSM equivalent circuit in the DQ-axis

From the (4)-(5), the developed torque (T_e) and the angular motor speed (ω_m) can be calculated in (6)-(7).



11) Wireless power transfer (WPT) is a technology that allows energy to be transmitted through an air gap to a load without any interconnecting cables. WPT is achieved through the inductive coupling between two coils, termed as transmitter and receiver coil. In EV charging applications, transmitter coils are buried in the road and receiver coils are placed in the vehicle.

WPT systems have at least two magnetic couplers:

Primary coupler: Located at the sending side

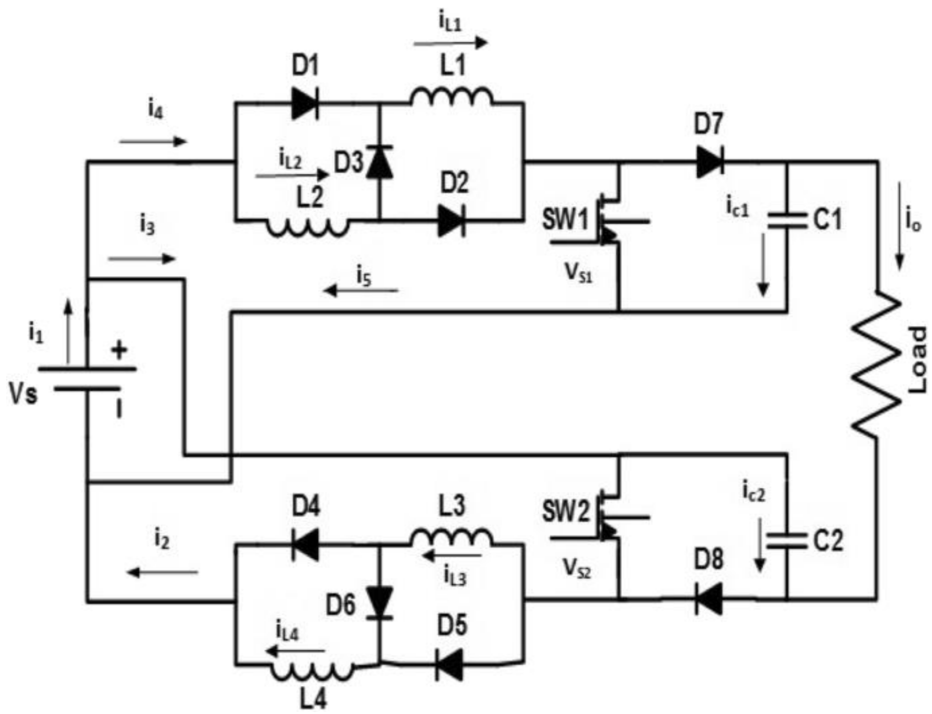
Pickup coupler: Located at the receiving side

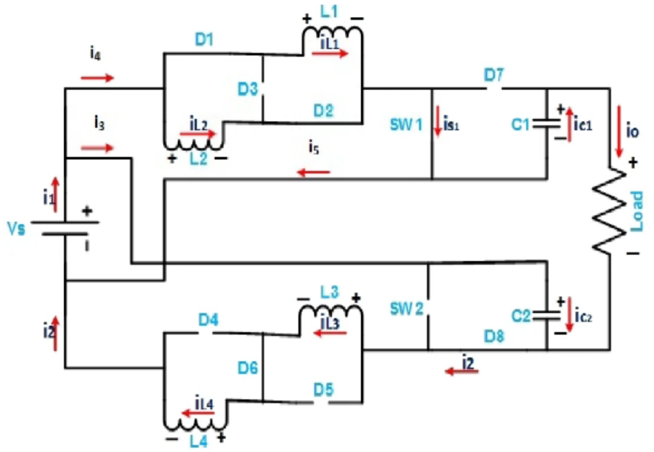
The magnetic coupler in a WPT for an EV could be either a pad or a track form.

WPT can provide power from an AC source to compatible batteries or devices without physical connectors or wires. The removal of ports and cables makes products less obtrusive and makes the recharging or powering of devices more convenient.

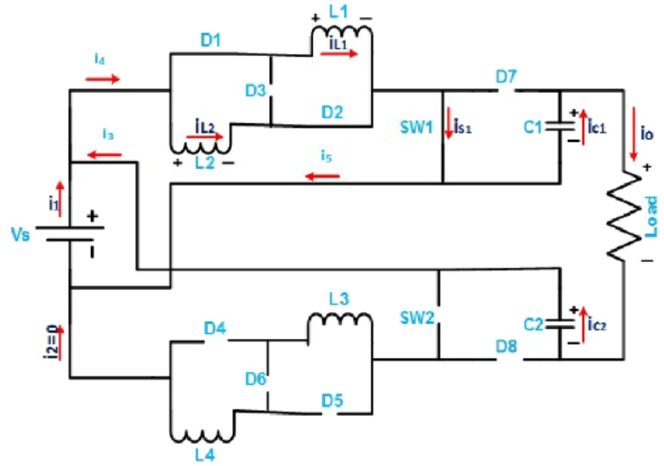
The power level is based on vehicle speed and its requested charging energy. Lower power is used when vehicle speed is slow, and much higher power is used for faster moving vehicles.

13) The proposed converter is composed of two similar converters connected to the same source as shown in Fig. 1. Each converter has two inductors, one capacitor, four diodes, and one switch. The four inductors have the same magnitude. The two switches are controlled in 180° phase delay to each other simultaneously. The proposed converter works in four modes as presented in Fig. 2. The key operating waveforms of the proposed converter are displayed in Fig. 3.

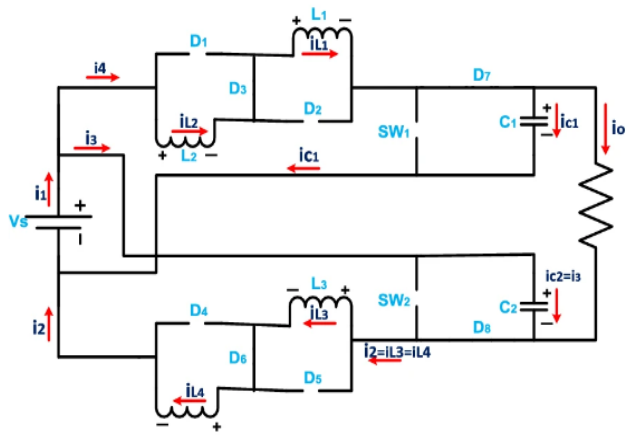




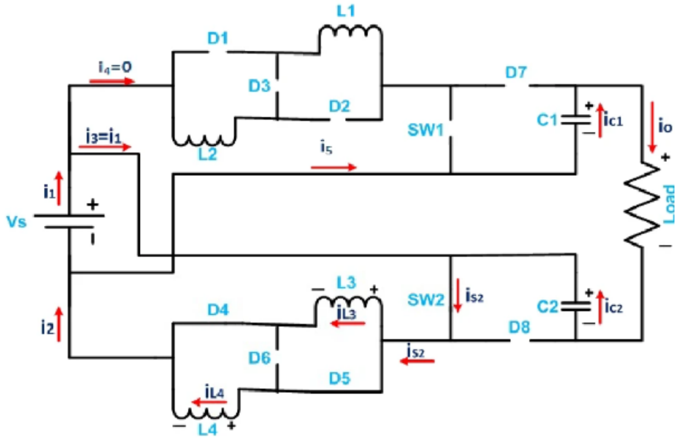
(a) Operating mode 1.



(b) Operating mode 2.



(c) Operating mode 3.



(d) Operating mode 4.

9) Battery characterization is the process of analyzing the characteristics of a battery. When selecting a battery, you should consider the following characteristics:

Type, Voltage, Discharge curve, Capacity, Energy density, Specific energy density, Power density, Temperature dependence.

The three main characteristics of a battery are:

Chemistry

Voltage

Specific energy (capacity)

The electrical characteristics of a battery define how it will perform in the circuit. The physical properties have a large impact on the overall size and weight of the product that it will power.

Some methods for characterizing batteries include:

Fourier transform infrared (FTIR) spectroscopy

Rietveld refinement X-ray diffraction

Neutron diffraction

Active Balancing Of Cells:-

- In active balancing during charging and discharging the cells transfer energy continuously to equalize the energy level in the cells.
- Different types of active cell balancing are capacitor based balancing, inductor-based balancing and power electronics converter-based balancing.
- In capacitor based balancing method an extraneous energy storage unit is there, a capacitor is used for shuttling the energy between the cells in the battery pack to attain equilibrium.
- In inductor or transformer based active balancing method it uses an inductor for transferring energy from various cells to pack or vice versa.

Passive Balancing Of Cells:-

- Passive balancing cell voltage equivalization is achieved in terms of SoC by delivering the energy over a resistor. It compares the cell of highest SoC level with the SoC levels of other cells and it absorbs the extra energy and discharges via the resistors and makes all the SoC equal.
- It is the easiest way of balancing the cells. Balancing is achieved by bringing the SoC of all the cells in the battery pack equal to the lowest SoC.
- Implementation and monitoring of passive balancing of cells are easy. In this method the efficiency is very less due to the energy loss via resistors.

Two types of passive balancing techniques are available
1. Fixed shunt resistor
2. Switched shunt resistor.