

Theories on the Propulsion System for Lithium-ion Battery Electric Vehicles with Infinite Cruising Range

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Abstract: On-board electric power generation in the absence of external energy may be sufficient to realize tough electric vehicles. The method to charge the Li-ion battery modules in the present investigation differs from the conventional single voltage source scheme in that the power requirement is only 12% of the power required for typical direct voltage applications. This method utilizes the ESI-PSC (electrostatic-induction potential-superposed electrolytic charge). The on-board electric power generation system is an identical twin of battery modules that function in ESI-PSC mode, in which the performance can be explained through consecutive cycles of field-induced charge and discharge between two batteries. When the charge of one battery is terminated, it becomes responsible for both the power to recharge the other battery and the power to drive the motor. This power generation system works with zero energy input, zero matter input and zero emission, without violating the laws of thermodynamics. The commercially available Li-ion battery modules and power control systems enable the realization of this type of EVs (electric vehicles). A simulation based on the official standard cruising mode (JCO08) showed that an electric vehicle with an on-board twin of 13.2 kWh energy capacity modules can travel 132 km before switching from charge to discharge.

Key words: EVs, lithium-ion battery, infinite cruising range, electrostatic induction charge, electrostatic energy, discharge capacity.

1. Introduction

The extraction of power from a charge-discharge energy cycle consisting of identical twin Li-ion battery modules has been considered theoretically to achieve a propulsion system as a solution to realize commercially viable EVs (electric vehicles) with infinite cruising range. The very high energy storage capacity of Li-ion rechargeable batteries is due to the electrostatic energy stored between the electrodes undergoing charge. Therefore, the main point of the particular mechanism of this power generation system is the principle of a “zero power input” electrostatic field created between the electrodes [1-5]. In this approach, it was our intent to change the method of energy supply to Li-ion battery modules from the conventional SSC (single-voltage source charge) scheme to an ESI-PSC (electrostatic-induction potential-superposed charge) scheme to enable electrostatic-to-chemical energy conversion.

The ESI-PSC directly converts the electrostatic energy into free energy of the Li embedded in the negative electrode, which enables the power requirement for charge to be reduced down to 12% of that required for SSC. Therefore, a highly positive power balance between charge and discharge can be achieved. To take advantage of this power difference, the CDRS (charge-discharge reciprocating system) consists of identical twin Li-ion battery modules. A typical Li-ion battery module for a commercial EV is divided into two identical modules. The charging of one module is conducted using the discharge capacity of the other module. When the discharge is terminated, the situation is changed between these modules. To design the CDRS, there is a necessary condition related to the charge time, in that one module must complete charge before discharge of the other module is finished.

Research on vehicles with infinite cruising range vehicle is nascent, and the underlying method was outlined in a previous paper [6]. However, many important items concerned remain unexplained. The

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present paper is an extended version that will be useful to make engineering decisions regarding this propulsion system.

2. Theoretical Background

2.1 Charging of Lithium-ion Battery Cell

The charging of a lithium-ion battery can be defined as an electrochemical process that is identified with electrolysis. Of various electrochemical cells, many cells exhibit the BP (barrier-potential) type of V - I characteristics shown in Fig. 1. The V - I curve typically shows the amount of current that passes through the

electrical circuit external to the cell from a voltage applied between the electrodes. The BP, V_B , is amount of voltage required to move electrons through the external circuit including a bias voltage source, and the effect of the BP is to oppose V_B as shown in Fig. 2 for the case of charging the Li-ion battery cells. These curves typically show the amount of current that passes through the power supply circuit external to the cell itself from a cell voltage applied to the electrodes. The null current voltage in the range from 0 to the barrier potential, V_B , contributes to a major portion of the total voltage applied to the cell (Fig. 3). Once the voltage

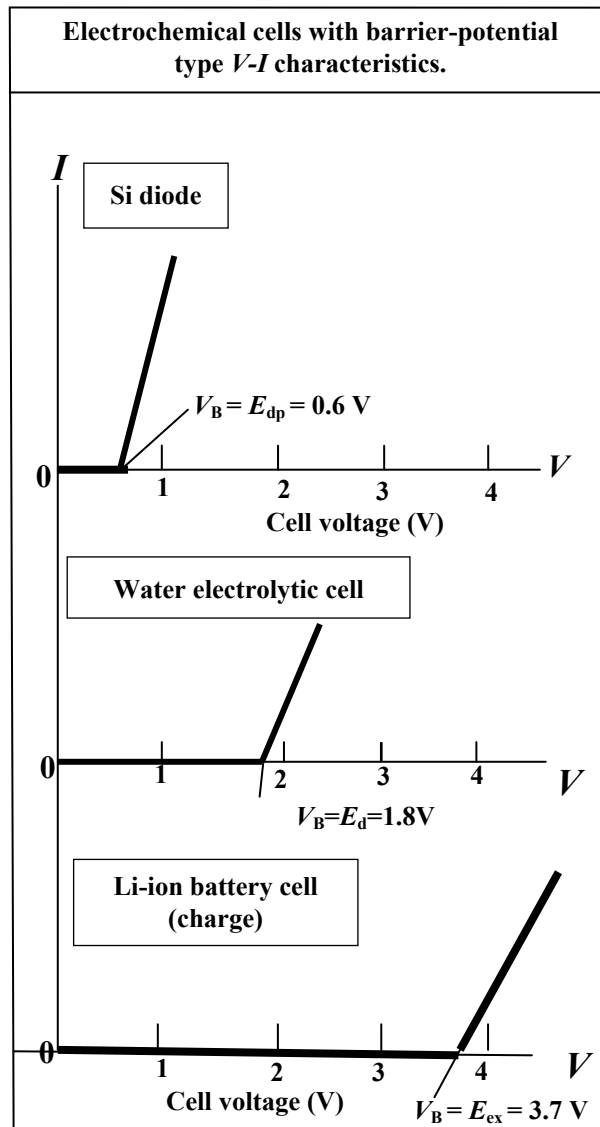


Fig. 1 Barrier-potential type V - I characteristics. E_{dp} : depletion voltage; E_d : decomposition voltage; E_{ex} : extraction voltage.

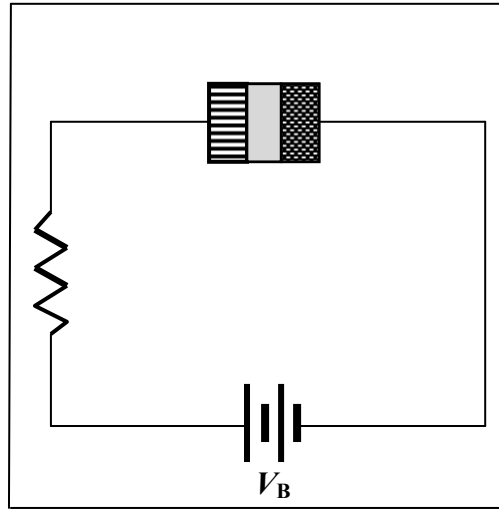


Fig. 2 Forward biased Li-ion cell. P: positive electrode; N: negative electrode; V_B : barrier-potential.

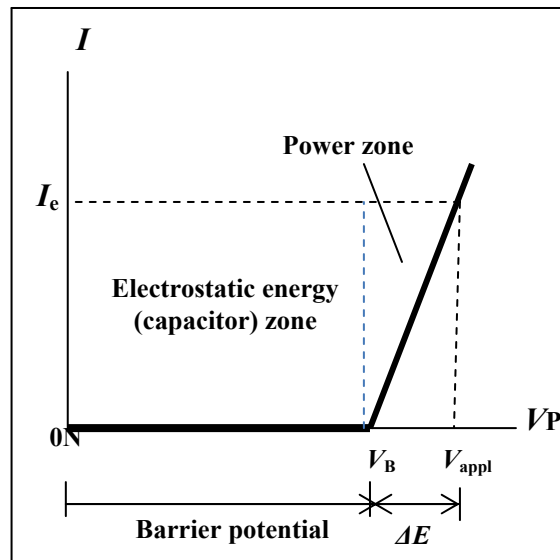


Fig. 3 Generalized V - I characteristics of the barrier potential type electrochemical cells. V_{appl} : total voltage applied to the cells; ΔE : extra-applied voltage over V_B .

reaches the transition voltage, the current begins to increase significantly. In the case of a Li-ion battery cell, this voltage is referred to as the Li-extraction voltage, E_{ex} , which is theoretically equal to the equilibrium potential of the coexistence of the two phases $\text{LiCoO}_2 + \text{Li}$, 3.7 V.

Fig. 4 represents the behavior inherent to the charge of the Li-ion battery cell [7, 8]. This V - I curve implies that the total cell voltage, E_{ch} , is the superposition of two separate voltages: (1) the practical voltage required

to extract Li^+ ions from the LiCoO_2 electrode, E_{ex} and (2) the additional applied voltage, ΔE , which when superposed on E_{ex} , yields the charge current, I_{ch} . ΔE is then identified with the electromotive force (*emf*) for the charge reactions to occur on the electrodes, and thus produces the charge current, I_{ch} . The voltage for extraction of Li from the positive electrode is a limit to the null-current static condition, so that it is identified with the barrier potential [9-12].

When electrons are extracted from the positive Li-oxide

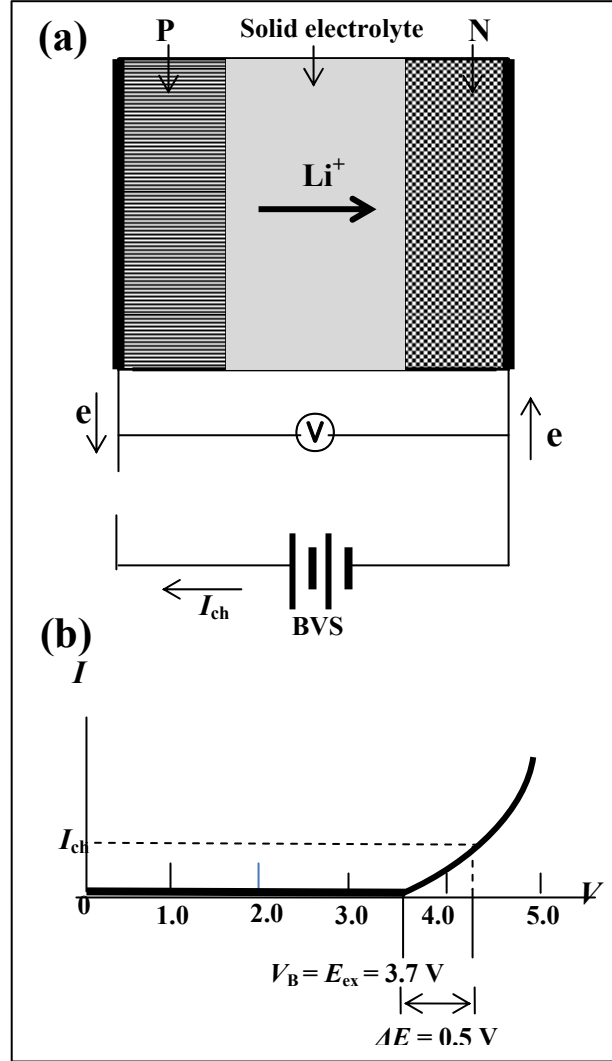


Fig. 4 Schematic diagrams showing the performance of the barrier-potential type Li-ion cell charge. (a) Cell performance. BVS: bias voltage source; I_{ch} : charge current. (b) The V - I characteristics of charge. E_{ch} : charge voltage.

electrode, the Li^+ ions leave the electrode/electrolyte interface. The Li^+ ions then migrate through the solid organic solvent electrolyte from the positive to the negative electrode, where they are embedded in a graphene sheet (porous carbon) by accepting electrons from a metal electrode plate. Fig. 5a shows the currents in the Li-ion battery cell during the charge operation. When undergoing charge, the free electrons delivered by the power supply located outside the cell can only exist in the conductive leads and electrodes. The electrons do not have solubility in the body of the electrolyte; therefore, the electrons can react with Li ions only at the electrode/electrolyte interface. The

power supply provides power for these reactions. Most of the electrons are stopped at the electrode surfaces. The same magnitude of ionic current flows through the electrolyte by migration due to the electrostatic field created between the electrodes. As a result, electrostatic energy is stored between the electrodes, specifically in the electrical-double-layers at the electrolyte/electrode interface. The energy stored at E_{ex} is described by the electrostatic-to-chemical energy conversion equation [3]:

$$\Delta G = (1/2)\nu \epsilon E_{\text{ex}}^2 \quad (1)$$

where, ΔG is the free energy of the Li stored between the electrodes by charging of the battery, ν is the volume

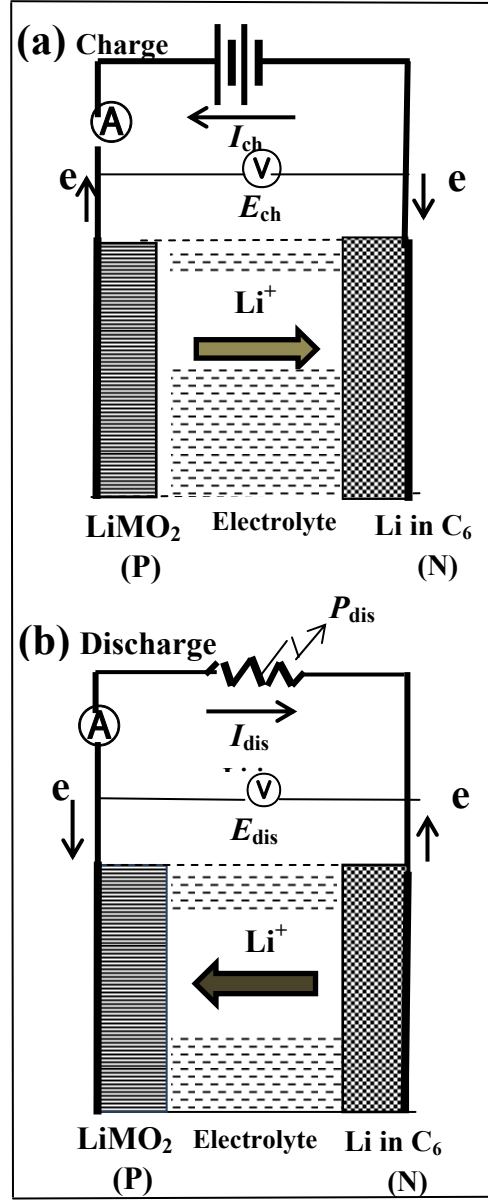


Fig. 5 Schematics of Li-ion batteries showing the performances. (a) Charge. M: metal element; I_{ch} : charge current; E_{ch} : Charging voltage. (b) Discharge. I_{dis} : discharge current; E_{dis} : discharge voltage.

of the electrolyte, and ϵ is the permittivity.

Fig. 5b shows the current in the Li-ion battery cell during discharge operation. The electronic current flows through the load to produce power. The same magnitude of ionic current flows through the electrolyte by migration due to the electrostatic field created between the electrodes.

2.2 Electrodynamic Foundation

The electrostatic-to-chemical energy conversion

expressed by Eq. (1) contributes to the consistency of the present power generation system, because in the electrostatic energy conversion associated with the Li-ion battery charge, the power supply external to the cell does not need to provide power to the cell, but merely a time-invariable voltage to the electrodes. Confirmation of this based on simple electrodynamics is given as follows.

Fig. 6 is the electrodynamic representation of the process that occurs between the electrodes.

Electrostatic energy results from conservative coulombic forces and is associated with the configuration of a particular set of point charges within an electrodynamic system with time-invariant electric field as shown in Fig. 6.

Electrostatic energy, U , of one point charge Q at position r in the presence of a point charge q , with infinite separation between the charges as the reference position, is described as:

$$U = k_c(qQ/r) \quad (2)$$

where, k_c is Coulomb's constant and r is the distance between the point charges, q and Q .

The power supply cannot provide power for the migration of Li^+ ions in the electrolyte, but only provides a constant voltage, E_{ex} , to the electrodes. The ions are transferred toward the negative electrode in the applied electric field, E , established by the static electrons on the electrode surface. Therefore, the migration of ions is expressed as a function of the electrostatic field strength [13-16]:

$$I_j = |z_j|FAu_jC_j(\partial\phi/\partial x) \quad (3)$$

$$E = -(\partial\phi/\partial x) \quad (4)$$

where, ϕ is the electric potential in the electrolyte, z_j is the charge number for species j , F is the Faraday constant, A is the electrode surface area, u_j is the mobility of species j , and C_j is the concentration of j . Eq. (3) implies that the ionic current flows under the influence of the electrostatic field established between the electrodes and the exerted coulombic force. Therefore, the total energy required for the charge of

the Li-ion battery is given by:

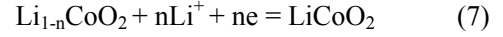
$$W_T = I_{\text{ion}}E_{\text{ex}} + I_{\text{ch}}\Delta E \quad (5)$$

where the first term, $I_{\text{ion}}E_{\text{ex}}$, may be called a zero power input electrostatic energy, in that the power supply is not required to provide power, but only the time-invariable voltage, E_{ex} , to the electrodes. Therefore, the actual power requirement to charge the Li-ion battery cell can be expressed by Eq. (6) in the absence of electrostatic term, $I_{\text{ion}}E_e$

$$P^* = I_{\text{ch}}\Delta E \quad (6)$$

2.3 Discharge of Lithium-ion Battery Cell

The oxidation reaction is performed during discharge:



When undergoing discharge, the Gibbs free energy change in Eq. (1), ΔG , is entirely converted to the power at the load. Fig. 5b shows the electronic current in the external circuit and the ionic current in the electrolyte. The constant output voltage of discharge, E_{dis} , theoretically equals the $\text{LiCoO}_2 + \text{Li}$ two-phase coexistence potential of 3.7 V, which produces the discharge current, I_{dis} , which passes through the load and generates the power, $E_{\text{dis}}I_{\text{dis}}$. The Li^+ current flows in the electrolyte due to the electrostatic field established by the time-invariable voltage between the electrodes, $3.7V$. ΔG is totally used in the load, therefore, there is no power for the Li^+ ion migration process. This may also be a positive proof of zero power input electrostatic energy.

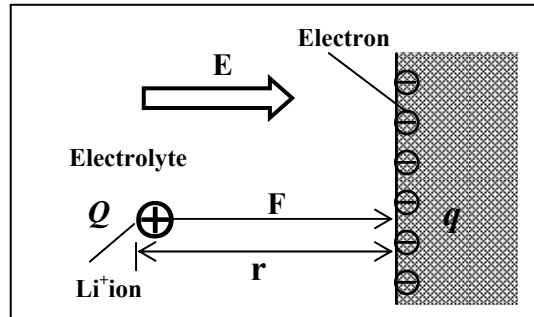


Fig. 6 Electrodynamic system of electrostatic field. E : field strength; F : Coulomb force, r : distance between two charges; q : charge on the electrode surface; Q : charge of ion in the electrolyte.

3. Electrostatic-Induction Potential-Superposed Charge

To conduct charge of the Li-ion battery cell, the external power supply must supply the voltage, E_{ch} , for the passage of charge current, which is defined as:

$$E_{ch} = E_{ex} + \Delta E \quad (8)$$

When the charge current, I_{ch} , flows by the application of E_{ch} , the product $E_{ch}I_{ch}$ represents the total power that the power supply is required to provide:

$$P = I_{ch}E_{ex} + I_{ch}\Delta E \quad (9)$$

The first term, $I_{ch}E_{ex}$, represents the power provided by the source to the free electrons in the external circuit to overcome the barrier potential before the cell conducts. The current, I_{ch} , flows due to the *emf* equal to ΔE , and not $E_{ex} + \Delta E$, so that the second term, $I_{ch}\Delta E$, is the power consumed in the battery cell. Thus, the electrical energy required by the conventional SSC is the total power. Most Li-ion batteries are charged to 4.2 V which is only 0.5 V ($=\Delta E$) higher than E_{ex} (3.7 V), thus the power required by Eq. (9) is $P = 4.2I_{ch}$. However, the net power required by Eq. (6) is $P^* = (4.2 - 3.7)I_{ch} = 0.5I_{ch}$. Therefore, (P^*/P) is $0.5/4.2 = 0.12$. In view of the principle of zero power input electrostatic energy, the charge power may be able to be reduced down to the level of 12% of the conventional power requirement, but only if there is a power supply method that enables elimination of the barrier potential effect.

For this purpose, we have developed the ESI-PSC system. Fig. 7a shows the experimental apparatus that was used in the previous work [5]. Fig. 7b shows the equivalent circuit applied to the case of Li-ion battery charging. This method supplies potentials to the electrodes in a dual mode, i.e., the superposition of two voltages on the electrodes with two independent voltage sources: one is a bias-voltage source PS1, which induces E_{ex} at the cell electrodes and the other is a power supply PS2, which provides power to the cell. These sources can act in parallel independently, and supply the cell electrodes with individual potentials,

which yields a superposition such that the resulting voltage between the cell electrodes equals the magnitude of the algebraic sum of the individual potential, i.e., $E_{ex} + \Delta E$. Fig. 7b is an equivalent closed circuit with two voltage sources connected in opposing directions. The performance of the cell can be explained by a series of steps. First, when the PS2 output voltage $V_{PS2} = E_{ex}$, $I_{ch} = 0$ (null point) because of the usual condition of uniformity of the electrochemical potential throughout the electrolyte solution [17]. Second, if V_{PS2} is increased from the null point, then a charge current, I_{ch} , flows due to the total source voltage (*emf*) of $\Delta E = V_{PS2} - E_{ex}$. Hence, the two sources can be replaced by a single source (PS2) that delivers ΔE . The bias-voltage-source does not need to produce an electrical current, but only a static voltage because of the null-current condition at E_{ex} . The cell voltage E_{ch} , is the superposition of ΔE on E_{ex} , and the entire corresponding charge process is the superposition of the electrode reaction process where ΔE is applied (i.e., where power is used) to the electrostatic process where E_{ex} is applied (i.e., where power is not used). If the charge current $2F$ (where F is the Faraday constant) flows to produce 1 mole of Li, and the current efficiency is almost unity, then the total power requirement reduces to the generalized form for any given cell, regardless of the extraction voltage E_{ex} , temperature, pressure, composition of the electrolyte solution and cell dimensions:

$$P^* = 2F\Delta E \quad (10)$$

4. Lithium Redox Electric Power Generation System

The Li redox electric power generation system consists of the charge and discharge cycle of Li-ion battery cell. The charge performs the electrostatic-to-chemical energy conversion based on the $Li^+ + e = Li$ reduction reaction at the negative electrode. The discharge performs the chemical-to-electrical power conversion based on the $Li = Li^+ + e$ oxidation reaction at the positive electrode.

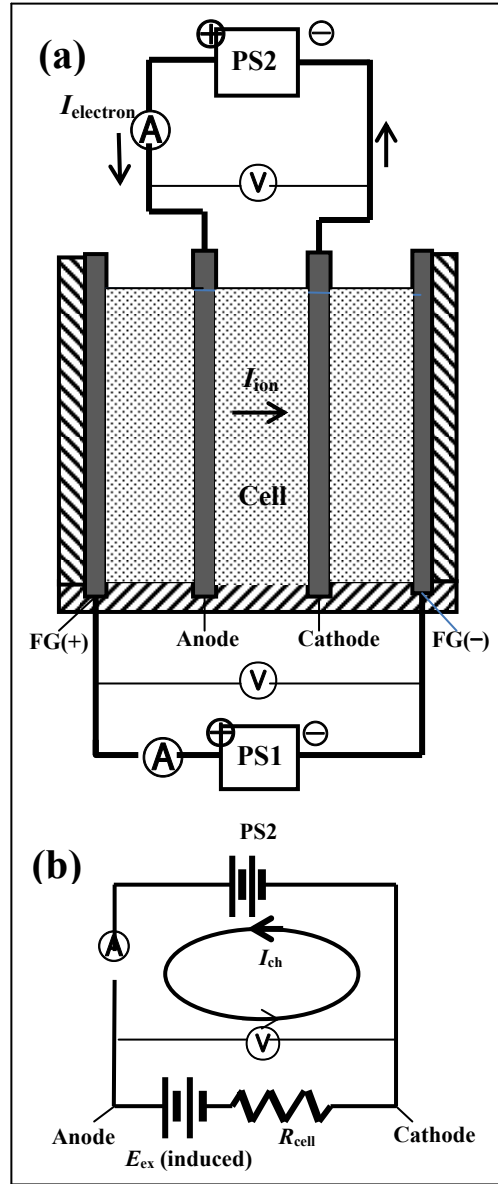


Fig. 7 ESI-PSC. (a) Experimental apparatus. PS: power supply; FG: field generator. (b) Equivalent circuit. R_{cell} : cell resistance; $E_{\text{ex (induced)}}$: induced extraction potential.

Therefore, a pair of the charge and discharge processes forms the Li redox cycle power generation system. If identical twin Li-ion battery modules constitute the LREG (Li Redox Electric Power Generator), and if the ESI-PSC is applied to charge the other module, then a highly positive power balance of the cycle may be obtained such that only 12% of the capacitive energy is used inside the cycle during charging process, and the remaining 88% can be provided outside the cycle to drive a motor (Fig. 8).

This study provides many theoretical aspects on the LREG. This is important because otherwise this thermodynamic cycle generator could be incorrectly mistaken for a perpetual motion machine that functions without the introduction of an external energy source. The LREG may be called a pseudo perpetual motion machine. This Li-ion battery power generation system can be viewed as a closed combined energy cycle of an ESI-PSC module performing the charge process and an identical module performing the discharge process.

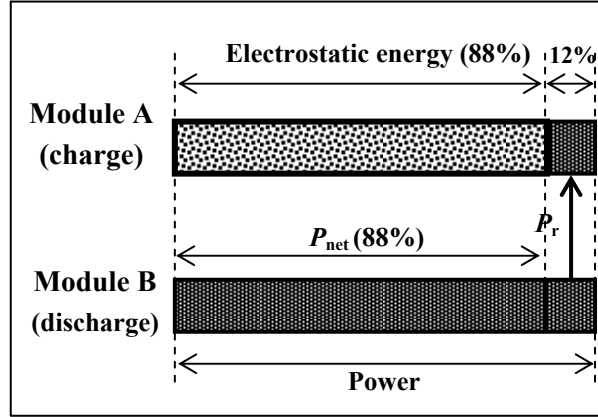


Fig. 8 Charge-discharge relationship in terms of energy. P_r : power returned to charge module A; P_{net} : net power output at discharge.

The sum of the zero power input electrostatic energy plus the power recycled from the discharge module is converted into the total power output from the discharge module. The total energy delivered by the discharge module equals the total energy required by the charge module; therefore, the zero power input electrostatic energy must be responsible for the power that can be extracted from the generator. Thus, the overall energy balance does not violate the energy conservation law.

5. Charge-Discharge Reciprocating Energy Cycle of Li-ion Battery Modules

5.1 Power Requirement of Charge

The basic construction of the series-connected Li-ion battery cells and the external circuit of the LREG system are shown in Fig. 9. The ESI-PSC consists of a combination of electrostatic induction and electrode potential superposition. The electrode potential of any individual cell in the module is given by the electrostatic induction. The outermost pair of electrodes acts as a field generator, and these electrodes are connected to power supply, PS1, while the electrodes next to the field generator electrodes are connected to power supply PS2 with the opposite polarity. There is no need for lead wires to carry the current from each inner cell. PS1 is employed to induce a potential, E_{ex} , in $(n-1)$ series cells, and the total

potential between the first and n th electrodes is $(n-1)E_{ex}$. When a voltage of $(n-1)(E_{ex}+\Delta E)$ is applied between these electrodes using PS2, which has polarity opposite to that induced by PS1 (i.e., $(n-1)E_{ex}$), an *emf*, ΔE , appears at each cell due to potential superposition. Thus, the charge current, I_{ch} , flows through the circuit due to the total *emf*, which is equal to $(n-1)\Delta E$ as a result of the superposition theorem, as shown by the equivalent circuit in Fig. 9c. Therefore, the power requirements of the external power circuit for the ESI-PSC mode are given by

$$P^* = I_{ch}(n-1)\Delta E \quad (11)$$

On the other hand, the discharge module delivers the power given by,

$$P_{dis} = I_{ch}(n-1)(E_{ex}+\Delta E) \quad (12)$$

Then, the P^*/P_{dis} ratio is written as

$$P^*/P_{dis} = 1/(1+E_{ex}/\Delta E) \quad (13)$$

The Li-ion batteries are usually charged to 4.2 V. Therefore, $P^*/P_{dis} = 0.12$, which may indicate that the module can finish the charge only by 12% of total amount of power delivered by discharge of the other module. Notice that PS1 must be disconnected during discharging operation.

5.2 Charge-Discharge Reciprocating System

A full charge is not required for cell durability reasons, therefore, an SOC (state of charge) of 80% is selected. For the same reason; a DOD (depth of discharge)

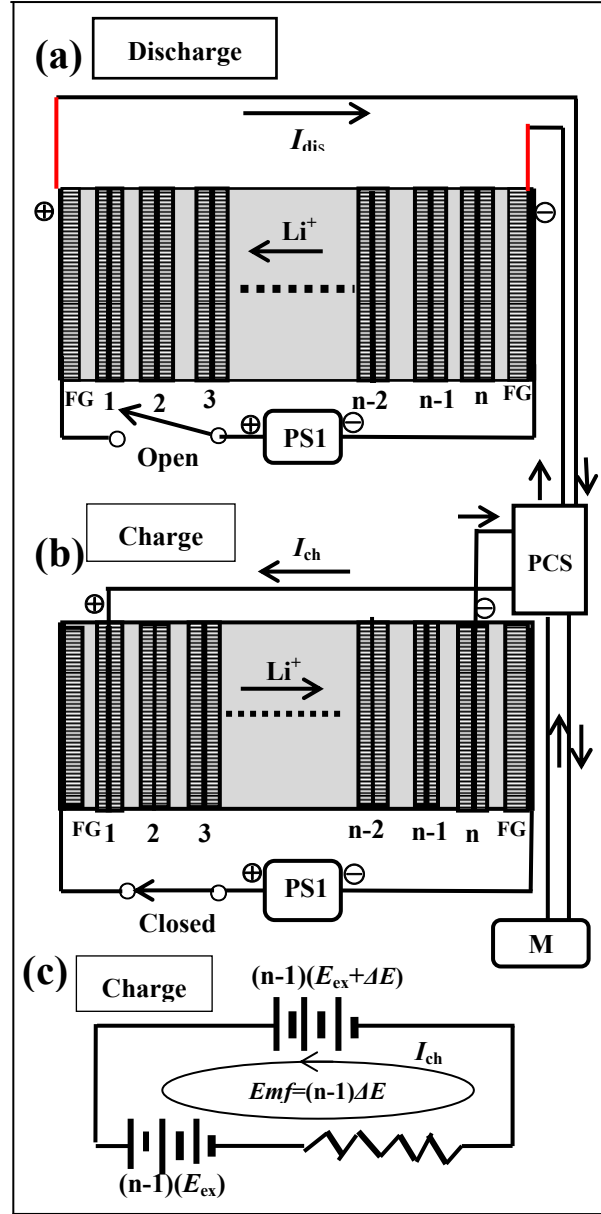


Fig. 9 LREG system in operation. (a) Discharge. (b) Charge. PCS: power control system; n : number of cell electrode; M : motor. (c) Equivalent circuit for charge.

of 80% is also selected. When the module is charged in the conventional way with a constant charge voltage of 4.2 V and a charge current of Q (Ah), the power used is $4.2 Q$ Wh per cell. However, when the same module is charged with the ESI-PSC mode, the power used per cell becomes $(4.2-3.7)Q$ (Wh) = $0.5 Q$ (Wh), which is 12% of that used for SSE.

The CDRS (charge-discharge reciprocating system)

consists of identical twin Li-ion battery modules as shown in Fig. 10. The charging of one module is conducted using the discharge capacity of the other module. When the discharge is terminated, the situation is changed between these modules. There is a necessary condition related to the charge time, in that one module must complete its charge before discharge of the other module is finished.

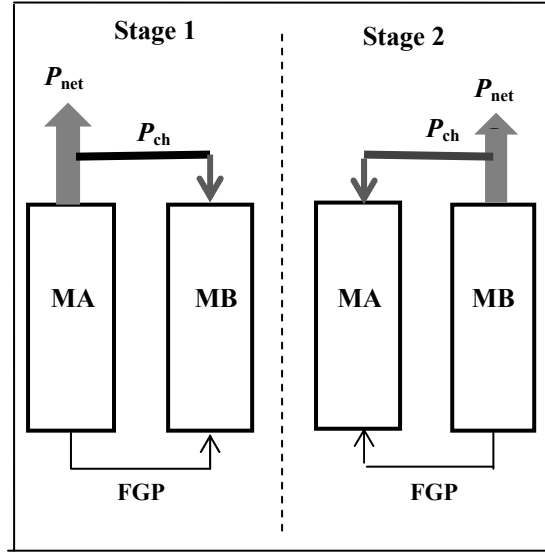


Fig. 10 Power generation system. MA: module A; MB: module B; P_{net} : net power output; P_{ch} : charge power; FGP: field generator potential.

5.3 Performance of CDRS

To simulate the performance of the CDRS, we theoretically examined a 50 kWh module for passenger EVs. The CDRS thus consists of two identical 25 kWh modules. Fig. 11 shows a charge-discharge cycle for one module. The vertical potential line at E_{ex} (3.7 V) is the standard discharge line that the quasi-static discharge follows. However, in practice, the output voltage of the cell goes down even below the standard line as the discharge proceeds. This effect may be attributed to polarization of the positive electrodes. If the rate of L^+ ion migration overcomes the rate of the electrode reactions for the ions to enter the oxide lattice, then an electrical double layer is formed at the oxide/electrolyte interface. Therefore, the departure of the cell potential from the equilibrium value upon passage of an ionic current increase with the discharge current. A full discharge is not desirable for reasons of cell durability, as in the case of charging.

If the charge and discharge cycle is performed with both SOC and DOD of 80%, then 40% of 25 kWh is

subtracted to give 15 kWh as a practically useful discharge capacity. Furthermore, 12% of 15 kWh, i.e., energy of 1.8 kWh must be returned to charge the other module. Thus, the net discharge capacity becomes 13.2 kWh. This capacity corresponds to the energy that can be used before switching the charge-discharge sequence. To estimate the cruising range with this capacitive energy, Fig. 12 presents the relationship between energy capacity and cruising range that has been investigated for the well-known passenger EVs of automobile companies around the world [18]. It is generally accepted that an EV can run 10 km with an energy capacity of 1 kWh, based on the official standard cruising mode (JCO08). If so, then the energy capacity of module A, 13.2 kWh, may permit a passenger car to travel 132 km before switching to module B. If the car runs continuously with a high speed of 100 km/h, then module B must finish being recharged within 1.32 h. This time interval is favorably much longer than that necessary to charge the amount of energy, 13.2 kWh, according to the present state of battery charge technologies.

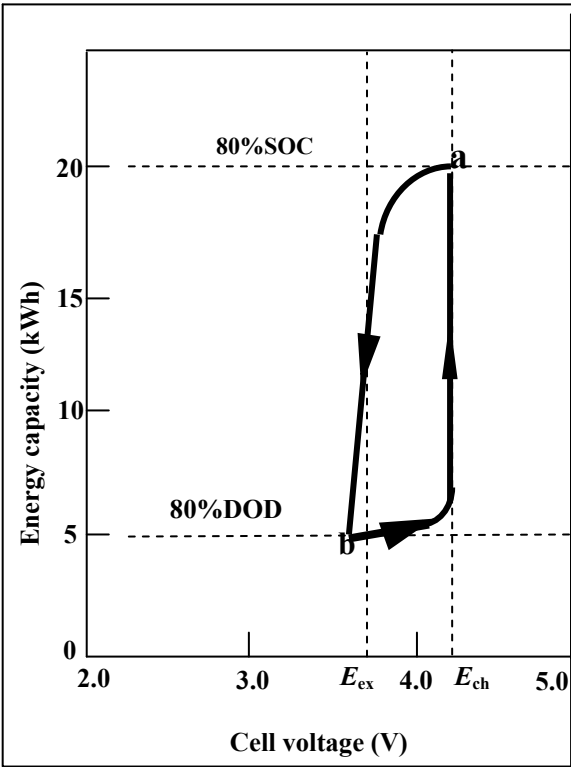


Fig. 11 Charge-discharge cycle of a Li-ion battery module.

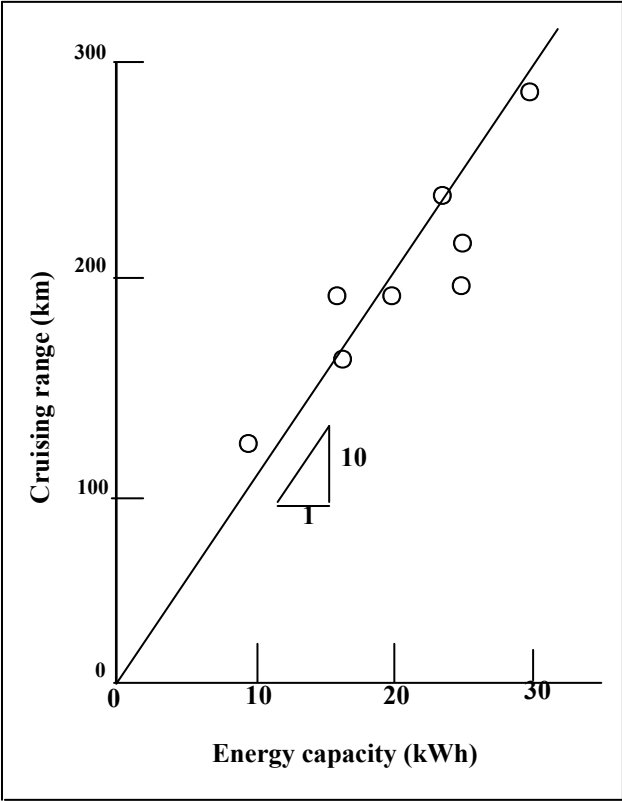


Fig. 12 Relationship between energy capacity and cruising range of the existing commercial EVs [18].

6. Applications

This type of generator in the absence of an external energy source appears to have a number of important potential applications. This approach is expected to be applicable to on-board power generators for buses, trucks, electric railways, ships and permanent portable power-generator. As high power applications, stationary type power generators at specific locations may also be potential candidates for application.

7. Materials

From an economic perspective, cobalt in the positive electrode is an expensive rare metal. The capability of energy storage is dependent on the value of E_{ex} as given by Eq. (1). Thus, ternary or quaternary Li oxides produced with less expensive transition metals such as Ni, Mn and Fe are now available [18]. The value of E_{ex} for these Li-oxides have been reported to be 3.3 and 3.4 V, e.g., E_{ex} for the quaternary Li ferrous phosphate is 3.3 V [19]. These materials may thus be applied for the present purposes.

8. Conclusions

We have performed a theoretical investigation of an on-board lithium-ion battery electric power generation system that can be operated on a mechanism of zero external energy input from outside the system. The electrostatic energy stored in the Li-ion battery cell is converted into power to drive a motor through two direct energy conversion processes; electrostatic-to-chemical energy conversion during charge and chemical-to-electrical energy conversion during discharge. This power generation system is expected to find practical application in future electric vehicles due to its simplicity, effectiveness, cleanliness and self-exciting characteristics.

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