Storage of Regenerative Breaking Energy in Electrical Vehicles

Umutcan Dogan[1], Gulgun Kayakutlu[2], Irem Duzdar[3]
[1]Engineering Management Dept., Istanbul Technical University, Macka, 34367 Istanbul, Turkey
[2]Industrial Engineering Dept. Istanbul Technical University, Macka, 34367 Istanbul, Turkey
[3]Industrial Engineering Dept. Duzce University Konuralp, 81620 Duzce, Turkey

***Abstract*--Electrical vehicles are the really important innovation for saving energy in the world. Electrical vehicles have electric motors and regenerative braking is used thanks to electric motor's generator/motor transition. In generator mode, regenerative braking energy storage can be used in motor mode. However, it includes many of hardware inside like battery pack. Battery pack has significant role for getting distance and it should be used carefully. Therefore, it is necessary to use additional device for recovering battery from high energy flow. When supercapacitor technology is used with battery, energy will be used more efficient and the overall battery life is increased. If the driver needs to have high energy, supercapacitor which is connected with battery in shunt, this connection type can enable to this situation. Because high energy means high current and supercapacitor structure is available to ensure this situation instead of battery thanks to low resistance without high temperature. There are some cases and scenarios about this connection. Therefore Case Based Reasoning Method is used in application. Simulation was created in Matlab/Simulink. To increase battery life and driving distance are essential goals in this project.**

I. INTRODUCTION

Nowadays, a conventional internal combustion engine with oil products has toxic gas emission. Traditional vehicles emit poisonous gases and they increase air pollution. It also increases the country's dependence on petroleum products to different countries. Therefore, price of petroleum products increases. At this point, electrical vehicle's popularities grow up. Also, nowadays almost all vehicle manufacturers continue own R&D studies to find more productive technologies.

Vehicles which have no electric motors couldn't do regenerative braking. Therefore, mechanic energy turns to heat energy; and it is released to the atmosphere. In electrical vehicles, motor can use it as a generator thanks to electric motor.

When brake pedal is depressed, electric motor turn into generator and it produces energy. But there is an acceleration limit and if brake unit exceed capability of generator, regenerative energy pass over heat energy.

Supercapacitor is used as a primary storage for regenerative braking instead of battery. If a battery is used to store this energy, battery cells will fail easily. Supercapacitor lifecycle is higher than battery. Battery has high internal resistance and when current flows in cells battery get hot quickly. Therefore, losses increase quickly and this situation cause to lower efficiency. In this situation, supercapacitor and battery are connected which is in parallel, can configure for getting more energy owing to expert system. Regenerative braking energy is calculated with Matlab/Simulink. Thus Cased Based Method can be used for finding more effective solution with experiences. Connection which is between battery and supercapacitor can configure expert system with Matlab Code.

II. REGENERATIVE BRAKING CONTROL

Braking force is very important parameter in electrical vehicles. If required braking force exceeds maximum braking force, difference between two parameters turn into conventional braking energy and it will be released to atmosphere.

When the speed of electrical vehicle increases, regenerative braking energy will be produced more than its standard. There is a lower speed limit in electrical vehicles because if electrical vehicle's speed falls down than the lower speed, motor couldn't turn into generator. In general, half of braking energy can be used as a regenerative braking energy.[6]

There is a relationship between deceleration and regenerative braking force. When braking force increases, electrical vehicle get more energy for usage in battery. However, maximum energy can increase up to motor/generator conversion parameter. Therefore in Fig.2, regenerative braking force decreases from 0,6g to 0,7g and motor/generator can't produce energy as from 0.7g as shown in Fig.2.

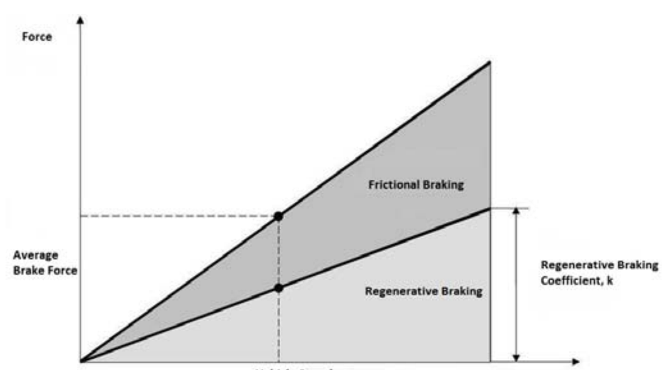

Fig. 1. Average Brake Force and Regenerative Braking Coefficient According to Vehicle Speed[2]

When the deceleration of vehicle increases, regenerative braking energy increases at the same time. But maximum regenerative braking point is the same with maximum generator torque.[6]

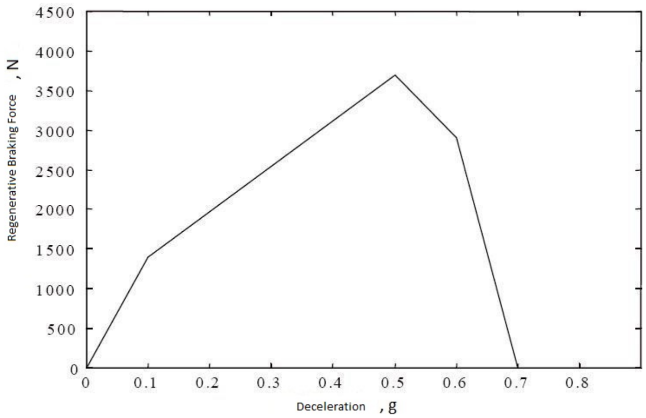

Fig. 2. Relation of Regenerative Braking Force and Deceleration [2]

III. SYMBOLISM

$n_{M/G}$=Motor Generator Efficiency Ratio
V= Speed(km/h)
r_r=Tire Radius(m)
n_t=Transmission Efficiency
a=acceleretaion(m/s^2)
k=Regenerative Braking Coefficient
f_b=Braking (Fractional) Coefficient
r_t=Wheel sidewall Thickness(m)
r_w=Wheel Radius(m)
m_w=Wheel Weight(kg)
m_t=Tire Weight(kg)
$I_{M/G}$=Motor Generator Inertia Moment($kg.m^2$)
C_D=Coefficient
A=Vehicle Front Area(m^2)
C_{rr}=Rolling Coefficient
m_f=Weight Coefficient in Front
g=Gravitational Acceleration(m/s^2)
p=Air Density(kg/m^3)
$P_{b,in}$=Transmitted Power to Battery and Supercapacitor(kW)

A. Regenerative Braking Equations

Regenerative braking energy is transferred to battery and supercapacitor. Energy is converted to power and it is specified as $P_{b,in}$. In order to find $P_{b,in}$, before (2), (3), and (4) should be calculated. Moment of inertia is calculated in Equation (2). Aerodynamic draft resistance force is calculated in Equation (3). Rolling resistance force is calculated in Equation (4).[2]

$$P_{b,in}=n_{M/G}.V(n_t n_f(kf_b(F_{aero}+F_{rr}+(m_v+4.I_{w/t}/r_r^2).a_x)+ I_{driveline}.(N_t^2.N_f^2/r_r^2.a_x)+I_{M/G}.(N_t^2.N_f^2/r_r^2.a_x)) \quad (1)$$

$$I_{w/t}=m_w r_w^2+m_t r_t^2 \quad (2)$$

$$F_{aero}=0,5.p.C_D.A.V^2 \quad (3)$$

$$F_{rr}=(C_{rr,front}m_f+C_{rr,rear}(1-m_f))m_v.g.\cos\alpha \quad (4)$$

B. Regenerative Braking Power Flow Diagram

Power flow diagram of front-wheel drive of an electrical vehicle is shown in Fig.3. Front and rear wheels' forces are seen in diagram. When vehicle driver presses on the brake, part of the braking energy convert to heat energy. Other part of the braking energy is used as regenerative energy owing to motor/generator conversion. In conversion, there can be some energy losses.

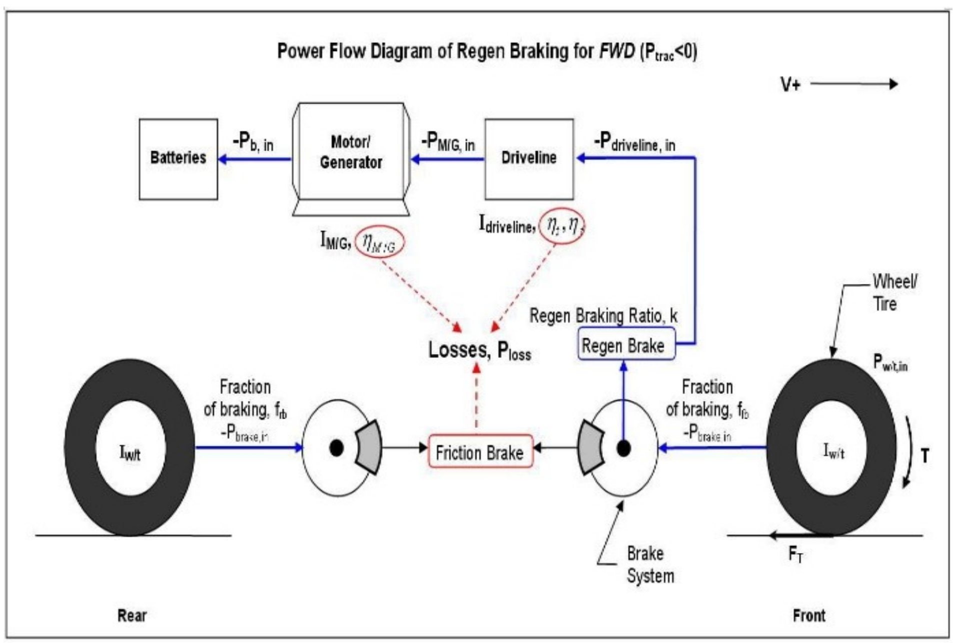

Fig. 3. Regenerative Braking Power Flow Diagram[2]

C. Data Modeling

Renault Zoe was used for modeling. Supercapacitor was selected according to battery voltage. Therefore, voltage was fixed as 400V.

IV. SUPERCAPACITOR CHARGE CONTROL WITH EXPERT SYSTEM

Expert system was written in Matlab/Script**.** Owing to expert system, supercapacitor and battery which is connected in parallel, control can be performed efficiently.

Electrical Vehicle's Battery:
Type = Lithium-ion
V(Voltage)=400V
I(Current.hour)=50Ah
12 Module
192 Cell
m(weight)=290kg

Supercapacitor:
(20 Units of 350F Supercapacitor is used in this simulation.)
Model - Type: Maxwell BCAP0350
V(Voltage)=2,5x150=400(V)
m(Weight)=60x150=9(kg)
R(Internal Resistance)=0,0032x150=0,48 Ω
C(Capacity)=350/150=2,33(F)
E(Total Energy)=186400(J)

Parameters:
$n_{M/G}$=0,85
V= Variable Speed(km/h)
n_t=0,95
n_f=0,95
a_x=Variable Acceleretaion(m/s^2)
k=0,5
f_b=0,6
m_w=7(kg)
m_t=9(kg)
r_r=0,32(m)
r_t=0,13(m)
r_w=0,19(m)
$I_{M/G}$=5,34 (kg.m^2)
m=1550(kg)
p=0,5
C_D=0,55
A=1,85(m^2)
$C_{rr,front}$=0,96
$C_{rr,rear}$=0,96
cosα=Variable Angle(rad)
m_f=0,6
g=9,81 (m/s^2)

V. SUPERCAPACİTOR CHARGE CONTROL WİTH EXPERT SYSTEM

Expert system was written in Matlab/Script**.** Owing to expert system, supercapacitor and battery which is connected in parallel can control efficiently.

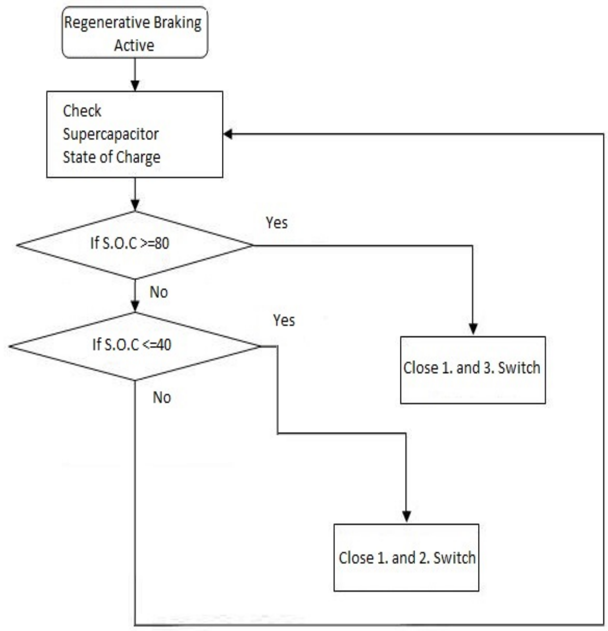

Fig..4. Control Algoritm

1. Switch = Charge
2. Switch = Load
3. Switch = Sccharge

While Load and Charge switches are closed, regenerative energy is stored to supercapacitor.
While Sccharge and Charge switches are closed, regenerative energy is stored to battery.
Initial situation of switches and other switch situations(S.O.C<40 and S.O.C>=80) are shown in Fig.5.

```
function [Load, Charge,SCcharge] = fcn(SOC)

    Load=1;
    Charge=1;
    SCcharge=0;
if (SOC >=80)
    Load=0;
    Charge=1;
    SCcharge=1;
end

if (SOC<40)
    Load=1;
    Charge=1;
    SCcharge=0;
end
```

Fig.5. Control Code

While battery is inactive, regenerative energy is stored in supercapacitor. If supercapacitor's S.O.C value exceed to %80, the next iteration should be. When supercapacitor's S.O.C value exceeds to %80, supercapacitor is switched off and battery is switched on for sharing energy. In discharge, when supercapacitor's S.O.C value is below than %40, supercapacitor is switched on and supercapacitor store energy again.

VI. SIMULATION RESULTS

Simulation Scenario:

While vehicle speed was 100km/h, vehicle driver presses on the brake with $2m/s^2$ acceleration and vehicle driver repeats this situation in three times on the inclined road. Produced power converted to energy. Electrical vehicle can travel approximately 1,7 km with 50 km/h constant speed. This scenario can be repeated again with different variables and get different results. Significant point is that gained distance can be calculated with only constant acceleration.

Regenerative braking energy are stored in supercapacitor, and when supercapacitor charge status is %80, switches position are changed as switched-off between supercapacitor and generator.

When supercapacitor switch position is changed as switched-off, between generator and battery connection is established again and remained energy is stored in battery. It is seen at x-axis (between 8 and 10) in Fig. 6 and Fig. 7. Storing energy in battery is slower than supercapacitor. Because battery has greater internal resistance than supercapacitor. Therefore, energy flow is seen slowly in battery.

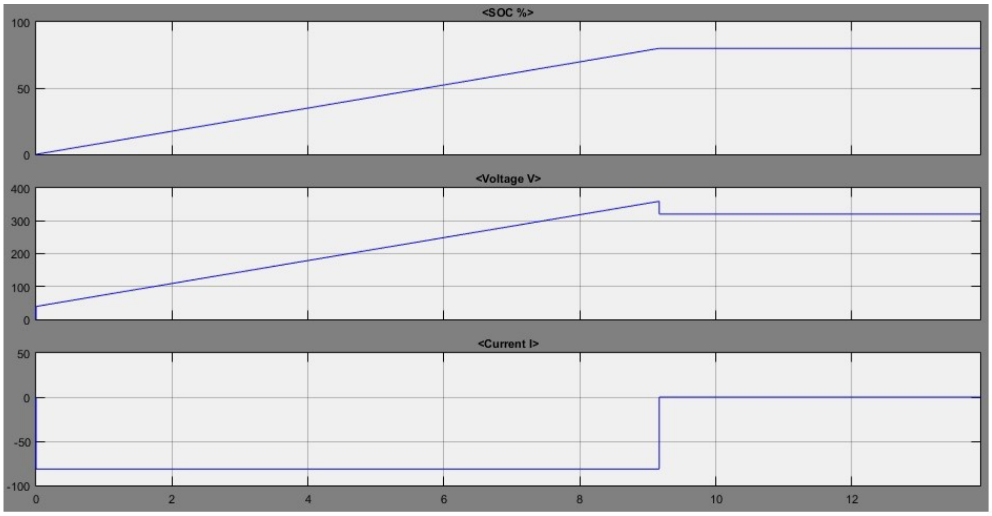

Fig.6. Battery Charge Simulation Supercapacitor Charge Simulation

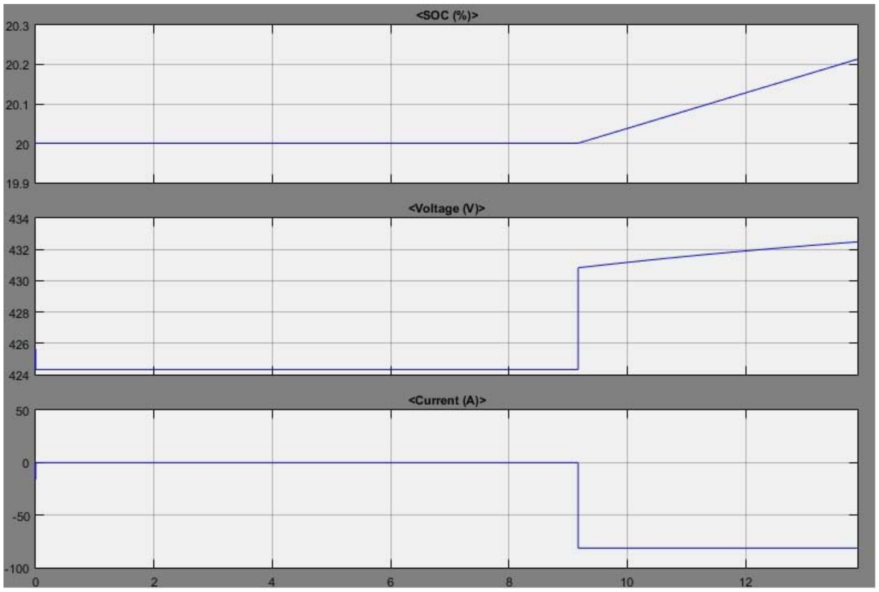

Fig.7. Battery Charge Simulation

VII. CONCLUSION

Regenerative braking is very important for electrical vehicles. Owing to driver, electrical engine works properly like a generator. Thus, energy is produced by engine and it is stored in battery and supercapacitor. Electrical vehicle speed is decreased slowly for productive using. So, supercapacitor is used as a temporary storage space. Owing to supercapacitor, system can provide abrupt current fluctuations and probability of damage to the battery is minimized. As seen in the results, when regenerative braking system and supercapacitor is used, productivity increase and electrical vehicle can store more energy.

Thanks to the electric motor that are used in electric vehicles, it protects nature and the environment does not release CO_2. In this way, it is protected against the release of natural gas. With the use of capacitors in the storage system in electric vehicles, the wear on the battery is reduced. As a result of this the amount of waste into the environment will decrease. Thus, nature will become less dirty and living standards will be maintained. Extravagant consumption will be prevented.

REFERENCES

[1] Chanthanumataporn, S., Sarawut Lerspalungsanti, Monsak Pimsarn: 'Design of Regenerative Braking System for an Electric Vehicle (EV) Modified from Used Car ' *, The Second TSME International Conference on Mechanical Engineering*, Krabi, 19-21 October, 2011.

[2] Lee, Jeongwoo: 'Rotating Inertia Impact on Propulsion and Regenerative Braking for Electric Motor Driven Vehicles', Blacksburg, Virginia, December 9, 2005.

[3] Noshin, O., F. V. Mulders , J. M. Timmermans , J. V. Mierlo , P. V. D. Bossche , H. Culcu; 'Effectiveness evaluation of a Supercapacitor-battery parallel combination for Hybrid Heavy Lift Truck', *Proceedings EVS. Vol. 24.* , Stavanger, Norway, May 13-16, 2009.

[4] Papanikolaou, N., John Karatzaferis , Michael Loupis , Emmanuel Tatakis: 'Theoretical and Experimental Investigation of Brake Energy Recovery in Industrial Loads ', *Energy and Power Engineering*, August 24, 2013.

[5] Renault Zoe Technical Specifications.

[6] Varocky, B.J (2011), 'Benchmarking of Regenerative Braking for a Fully Electric Car ' , Report No. D&C 2011.002.

[7] Zhang, Haoming, Yinghai Wang, Peh lian Soon: 'Application of Super Capacitor in HEV Regenerative Braking System', *The Open Mechanical Engineering Journal,* China, 2014.