The Development of Hybrid Electric Compressor Motor Drive System for HEV

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***Abstract*- The HEV (Hybrid Electrical Vehicle) becomes commercialized recently because of high fuel efficiency and low air pollution. The highest output power system except the traction motor is an air conditioner compressor in HEV system. The full or hybrid electric compressor is applied for HEV. The general HEC (Hybrid Electric Compressor) requires the half power motor and drive system of the full electric compressor because the rated output power of motor drive system is designed to charge the minimum cooling capacity at the time of idle stop. Therefore, this hybrid electric is more economical and practical solution. In this paper, we studied about the motor drive system of hybrid electric compressor for HEV. The applied voltage specification is 42 V, an IPMSM (Interior Permanent Magnet Synchronous Motor) is designed and applied as the compressor drive motor.**

I. INTRODUCTION

Recently the development of the next generation vehicle which is more efficient and less air pollution is accomplished actively. This next generation vehicle development divided as two axes, one is the HEV (Hybrid Electrical Vehicle) and the other is FCEV (Fuel Cell Electrical Vehicle).

Since a few years ago the HEV has been commercialized because of high fuel efficiency and low air pollution. It's forecasted by the economists that the HEV market is expanded very quickly and it accounts for the 7% of new vehicle market in 2010.

By this reason, the research concerning about the motor drive system for HEV especially the power train motor is actively carried out. The highest output power system except the traction motor is an air conditioner compressor in HEV system.

Since the engine is turned off at the time of idling stop mode in HEV system, the conventional air conditioner can not be operated in this period. In the hot summer it causes the temperature rising of the inside of car. There for electric driving type compressor system is necessary in the HEV [1] [2] [3].

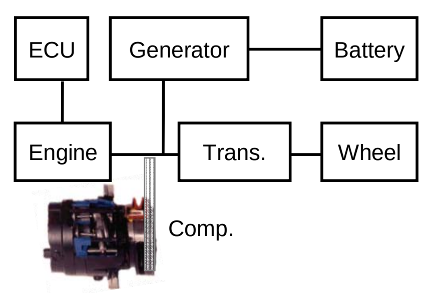
The full or hybrid electric compressor is applied for HEV. The general HEC (Hybrid Electric Compressor) requires the half power motor and drive system of the full electric compressor because the rated output power of motor drive system is designed to charge the minimum cooling capacity at the time of idle stop. Therefore, this hybrid electric is more economical and practical solution [4].

In this paper, we studied about the motor drive system of hybrid electric compressor for HEV. We accomplished design optimization of IPMSM (Interior Permanent Magnet Synchronous Motor) for 42V applied voltage system using the design tools of 6sigma. In addition, the designed motor is controlled by the suggested maximum torque control methodology. The driving performance of this motor drive system is measured and verified by the experiment.

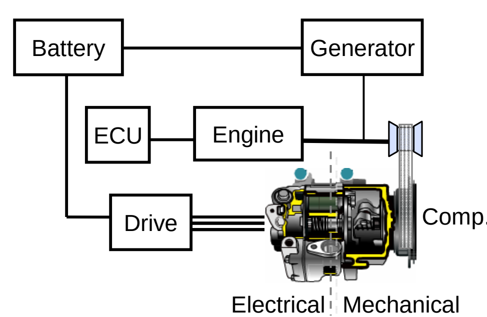
II. HYBRID ELECTRIC COMPRESSOR MOTOR SYSTEM

A. *Hybrid Electric Compressor*

The HEC system is configured as shown in Fig.1. In the Fig.1, (a) shows the conventional mechanical compressor system. In this system, compressor is driven by the motoring torque of engine via pulley belt, and the compressor cannot be operated at the time of idling stop mode of HEV. This is the week point of the mechanical compressor system in the application of HEV.



(a) Conventional mechanical compressor



(b) HEC (Hybrid Electric Compressor)

Fig. 1. System configuration of air-conditioner compressor

In the HEC system as shown in Fig. 1(b), the inner compression part is divided into two parts. One is that of electric motor and the other is that of mechanical power of engine. Due to this structural feature, in the HEC the driving torque is provided by the combination of the electric motor and the engine power.

In HEV system, the operation mode of air-conditioner compressor is shown in Fig. 2.

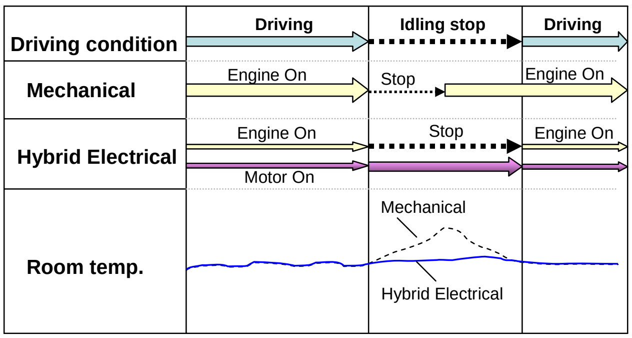


Fig. 2. Operation mode of compressor in HEV

In the application of conventional mechanical compressor to HEV, the operation of compressor is impossible at the time of idling stop. Within a short time the cooling air is provided by the stored cooling capacity of heat exchanger.

After a while, the room temperature would be going up and the engine should be turned on to lower room temperature. By this reason the fuel saving effect would be limited in the summer.

In the application of HEC, when the vehicle is running at the normal driving mode the compressor is driven by the sum of the engine power and the motor torque. And, the compressor is driven by the torque of motor only at the time of idling stop. Therefore, the air-conditioner can always provide cooling air to inside of car in the application of HEV.

III. Motor Drive System Design Optimization

A. *Motor Design Procedure*

In this study, PMSM (Permanent Magnet Synchronous Motor) is adopted as compressor driving motor for the high output power and high efficiency under low applied voltage condition.

The design procedure is shown in Fig. 3.

As shown in figure, the Motor specification is designed firstly considering system requirement specification. And then, the dominant design factor's range is set up by the E-L map. This E-L map is concerning about the correlation of inductance and back EMF to satisfy the required output characteristics. After that, the preliminary design is executed referring to the designed E-L map. Finally, the design optimization is accomplished by DOE (Design of Experiment) and RSM (Response Surface Method) those are the design optimization tools of 6sigma.

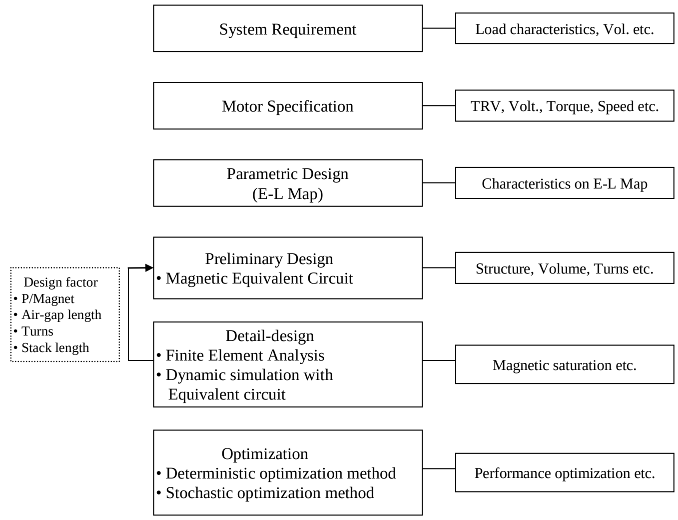


Fig. 3. Design process of electromagnetic structure

B. *System Requirement Design*

In this study, the applied voltage of battery is designed as 42V. The total full power rating of compressor is 4~5kW, and the power rating of electric motor is designed to 2kW which is the half of full power of compressor.

TABLE I
System Requirement

Item	Unit	Specification
System voltage	V	42
Rated output	W	2,000
Rated speed	rpm	3,500
Rated torque	Nm	5.7
Efficiency	%	Over than 90
Operating speed range	rpm	500~7,500
Cooling method		Suction coolant cooled

Table I shows the system requirement specification. Since higher current is needed for the required output power under low voltage system such as 42V. The optimal design to minimize the applied current is important for high efficiency and high power.

C. *Motor Design and Optimization*

1) TRV (Torque per unit Rotor Volume) determination

In the application of IPMSM, the typical value of TRV is designed 14~42 (kNm/m^3) under air-ventilation cooling condition [5]. This TRV value is dependent on the cooling method such as enforced ventilation or natural circulation. This TRV can be designed over than 50 (kNm/m^3) under the water cooling condition.

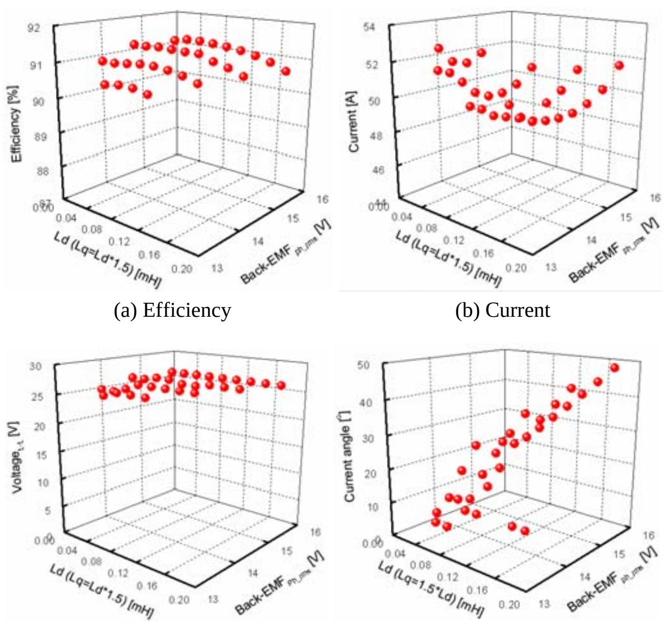
In this paper, TRV is designed as 30 (kNm/m^3) considering the coolant cooling condition; the motor is cooled by the suction coolant.

2) Preliminary Design

In IPMSM the design of back EMF E and inductance is very dominant design factor which determine output performance and efficiency characteristics.

The appropriate design range at the E-L map is designed as show in Fig. 4. In this design, the lumped parameter method analysis is utilized, and core loss is neglected.

The selected value of each parameter in the E-L map is qualified to be satisfied the system requirement as shown in Fig. 5, and the value of each factor is written in Table II.


(a) Efficiency (b) Current

(c) Voltage (d) Current angle

Fig. 4. Design area selection by E-L Map

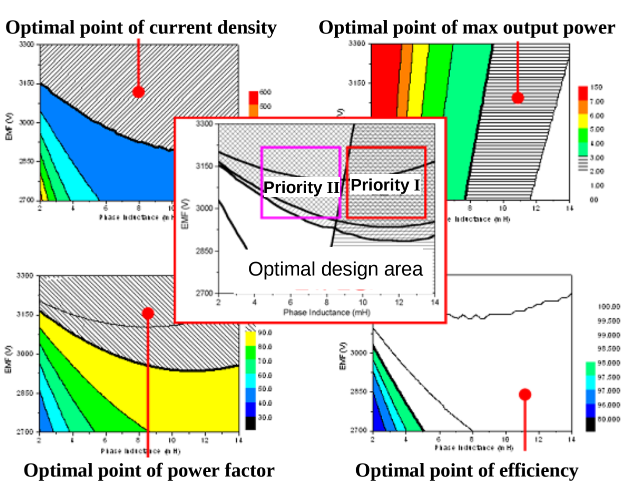


Fig. 5. Initial design point resulted by RSM

TABLE II

INITIAL PARAMETER DESIGN

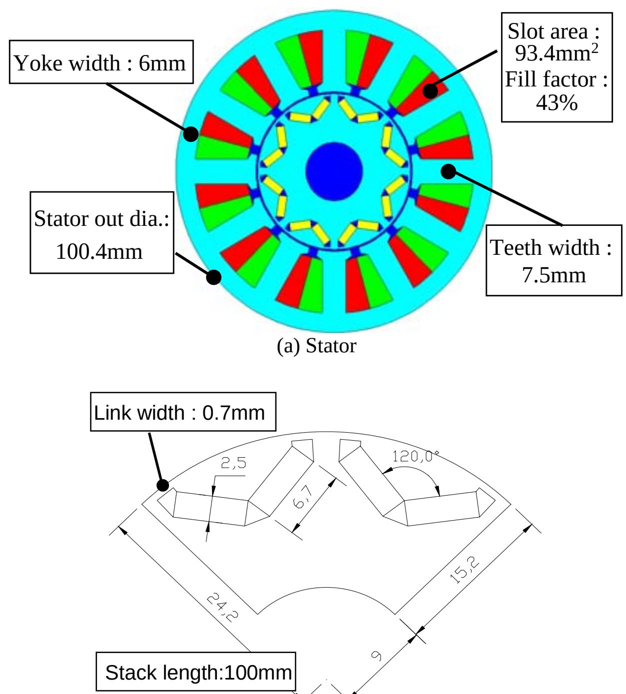
Item	E-L Map		Initial Design Value
	Parameter range	Max. efficiency point	
D-axis Inductance	0.01 ~ 0.2mH	0.09mH	0.099
BEMF(phase)	13 ~ 16V	15.4V	14.25V
Saliency (Lq/Ld)	1.5	1.5	1.63
Current	47 ~ 53A	48A	48A
Current Phase Angle	0 ~ 50 deg.	28 deg.	28 deg.

The preliminary structure is designed as shown in Fig. 6 by the following the referring of design value of Table II. This preliminary model would be the base structure and starting point of design optimization.

3) Optimization

The design optimization is accomplished by DOE (Design of Experiment) and RSM (Response Surface Method) in Fig. 7. The DOE is very useful to find the dominant and critical design factor for the performance characteristics. After finding of dominant design factor, it is optimized by RSM to be satisfied the required design objective.

Stator slot opening, flux barrier angle and chamfer dimension are selected as dominant design factor. Those factors are optimized to minimize torque ripple and cogging torque. The final structure is redrawn in Fig. 8.



(a) Stator

(b) Rotor

Fig. 6. Preliminary design structure

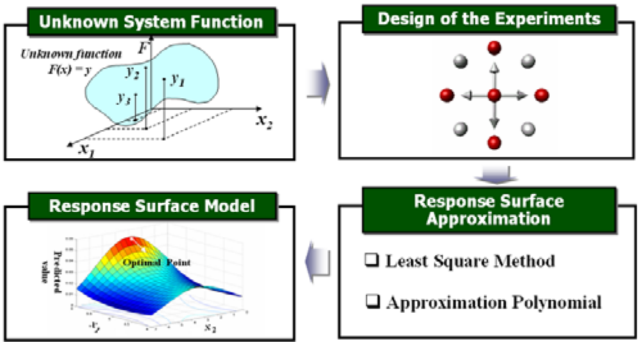


Fig. 7. Design optimization procedure

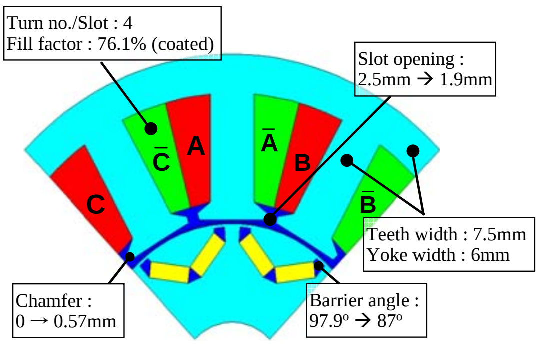
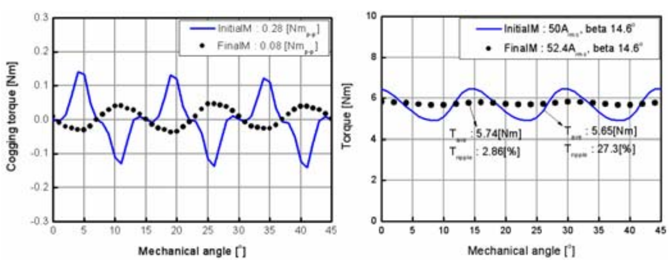


Fig. 8. The structure of final design



(a) Cogging torque (b) Torque ripple

Fig. 9. Performance comparison between initial model and optimized model

D. *Motor Control Unit Design and Maximum Torque Control*

In the inverter circuit design for low voltage and high power, the high current commutation is an important design consideration point. The MOSFET is selected for the high frequency switching device, and two MOSFET are connected in parallel to commutate high current. It can be a good solution for the economical feasibility and the reliability.

DSP TMS320F is used as a control processor, and the peripheral circuit is designed.

The Allometic 1 curve fitting method is utilized to simplify the nonlinear high order relationships between d-axis current and q-axis current for the maximum torque production per unit current.

The torque equation of IPMSM is able to be expressed to (1).

$$T_e = \frac{3}{2}\frac{P}{2}(\Phi_f I_s \cos\gamma + \frac{1}{2}(L_q - L_d) I_s^2 \sin 2\gamma) \qquad (1)$$

In (1), the magnetic torque is proportioned to cosγ which is the function of current phase angle, and the reluctance torque is proportioned to sin2γ . So from that, whole torque equation is determined. Fig. 10 shows the waveform is the torques by magnet and reluctance defending on the current phase angle γ .

In Fig. 10, when maximum torque is assumed as 1 at the point of maximum torque, the torque by permanent magnet is 70% of a total torque and reluctance torque is about 30% of a total torque. When γ is 0 deg., the magnetic torque is maximum. When γ is $\pi/4$, the reluctance torque is maximum. Because total torque which is the sum of magnetic and reluctance torques, the maximum value is between the two maximum torques.

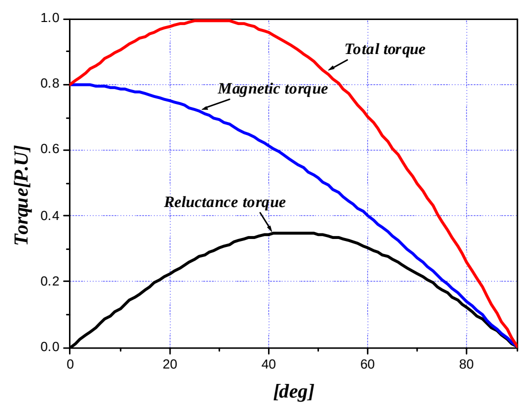


Fig. 10. Torque element of the IPM

The way of achieving maximum sum of magnetic torque and reluctance torque is "maximum torque per unit current control" method. The torque control is decided by the largest torque per unit current.

Getting maximum torque per unit current, equation (1) can be rewritten as

$$T_e = \frac{3}{2}\frac{P}{2}(L_d - L_q) i_q \left(\frac{\Phi_f}{L_d - L_q} + i_d\right) \qquad (2)$$

$$(i_d, i_q) = \left(\frac{\Phi_f}{L_q - L_d}, 0\right) \qquad (3)$$

The maximum torque is the function of q-axis current i_q and d-axis current i_d.

Fig. 12 is the locus of maximum torque per unit current. This functional relationship is very complicated to be used in the practical system. In this paper, to find the relational expression of the i_q and i_d current, the curve fitting method is used easily in microprocessor. The curve fitting method here uses the Allometic1 technique.

In Fig. 12, the black line shows the relationship of the d-q axis current and the red line shows the Allomitic1 curve fitting equation by (4) which is expressed by the five order function.

$$i_q = 3.2169 \bullet 10^{-6} \bullet i_d^5 + 3.16589 \bullet 10^{-4} \bullet i_d^4 + 0.0122 \bullet i_d^3 + 0.24359 \bullet i_d^2 - 2.260869 \bullet i_d \quad (4)$$

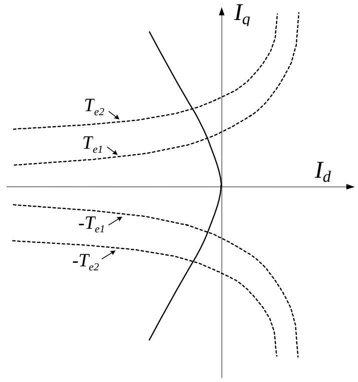


Fig. 11. The locus of maximum torque per unit current

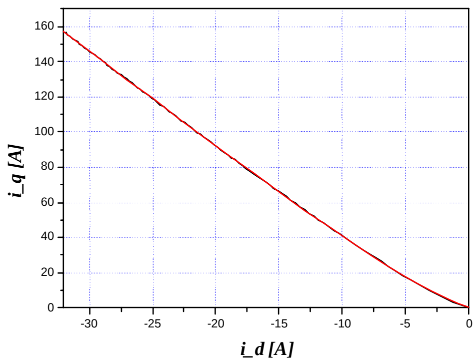
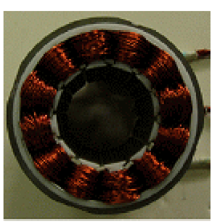


Fig. 12. Result of the curve fitting for maximum torque control

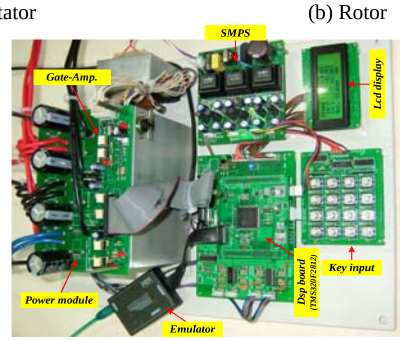
IV. Experimental Result

The prototype of IPMSM motor and drive system are implemented as shown in Fig. 13.



(a) Stator

(b) Rotor



(c) Rotor

Fig. 13. Photograph of prototype motor

The driving performance of this motor drive system is measured in the dynamometer.

The driving performance at the rated load point is showed in Table III, and the efficiency characteristic according to load torque variation is measured like as Fig. 14.

The high efficiency over than 90% is obtained in the experimental test.

Table III

Driving Characteristics at the Rated Load (3,500 rpm)

Item	Unit	Value
Pole numbers		S/T: 8, R/T: 12
BEMF (phase) @3500rpm	V	13.44
Cogging torque(p-p)	Nm	0.08
Copper loss	W	62.1
Core loss	W	102.1
Mechanical loss	W	61.3
Efficiency	%	90.3
Power factor	%	89.92
Inductance	mH	Ld : 0.096, Lq : 0.143
Terminal Voltage	V	26.7
Current	A_{rms}	52.35
Phase angle of current	deg.	14.6
Torque	Nm	5.74 (@50.2A_{rms})

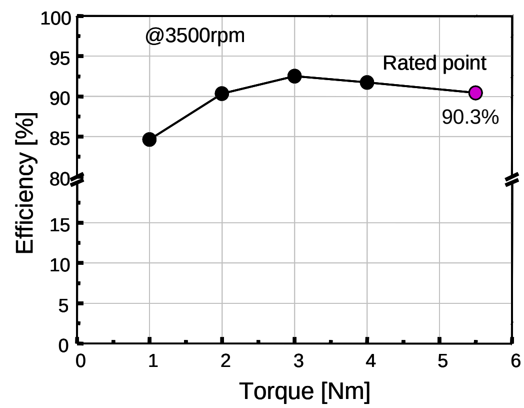


Fig. 14. Efficiency characteristics according to load torque

V. Conclusion

In this paper, the design result of IPMSM drive system for Hybrid Electric Compressor of HEV operated in 42V battery system is presented.

In the driving performance test, the rated driving characteristics and maximum output characteristics are ensured. The high efficient motor driving characteristic over than 90 % is achieved, and the test result of the implemented motor drive system is well matched with the required specification.

It would be a good development approach for the Hybrid Electric Compressor motor drive system.

Hereafter, we'd like to study about more high voltage (e.g. 180V) motor drive system in order to reduce motor volume and the current rating of power switch. It would be more applicable to be commercialized from the viewpoint of cost merit.

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Characteristic Analysis and Comparison of IPMSM for HEV According to Pole and Slot Combination
Jae-Woo Jung, Jung-Pyo Hong and Young-Kyoun Kim[1]; *Hanyang Univ., [1]Korea Electronics Institute, S. Korea.*

Investigation on Characteristics and Optimal Shapes of Interior PM Synchronous Motor for Electric Vehicle Application
Sung-Il Kim, Jung-Pyo Hong and Jin Hur[1]; *Hanyang University, [1]Korea Electronics Technology Institute, S. Korea.*

Development of an Electric Driven Pump Unit for Electro-Hydraulic Power Steering of 42V Automobile
Se-hyun Rhyu, Yong-kyoun Kim, Jun-hyuk Choi, Jin Hur and Doo-hyung Lee[1]; *Korea Electronics Technology Institute, [1]Hyundai MOBIS, S. Korea.*

Post-break session: 10:30 am – 12:00 pm

Dynamic Control of Hybrid Energy Storage System for Mild HEV
Baek Haeng Lee, Dong Hyun Shin, Hyun Sik Song[1], Jin Beom Jeong[1], Hee Jun Kim and Byeong Woo Kim[2]; *Hanyang University, [1]Korea Automotive Technology Institute (KATECH), [2]Ulsan University, S. Korea*

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Optimality and Reachability - Pseudo Boolean power Flows for multi-sourced Vehicle Topologies
George Kladis, John Economou, Antonios Tsourdos and Brian White*; Cranfield U.-Dept. of Aerospace Power and Sensors, USA.*