奨励金№1492

マルチモーター電気自動車のグローカル（グローバル／ローカル）エネルギー管理

グエン　ビン　ミン
東京大学　特任助教

Glocal (Global/Local) Energy Management for Multi-motor Electric Vehicles

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本研究は、マルチモーター型の電気自動車を想定し、グローバルなエネルギー最小化とローカルなトラクション制御を同時に満たすために、グローバルエネルギーマネジメントのための新しいフレームワークを提案する。電気自動車をマルチエージェントシステムとして扱い、階層分散制御構成を設計する。受動性制御と外乱オブザーバの実用的な手法を用いて、制御性能を向上させ、システム設計への負担を軽減する。提案するフレームワークの有効性は、いくつかの電気自動車プロトタイプによって評価が行われた。

Considering the multi-motor electric vehicles, this study is to propose an energy management framework to to simultaneously achieve the global objective of minimizing energy consumption, and the local objective of improving the safe traction at each local driving wheel. To this end, this study treats the electric vehicles as multi-agent systems and establish the hierarchically decentralized control configuration. The practical approaches of passivity control and disturbance observer are utilized to improve the performance while reducing the design burden. The effectiveness of the framework has evaluated using several electric vehicle prototypes.

1. 研究内容

1.1. Research achievement

1.1.1. Problem statement

An electric vehicle (EV) is a system that exchanges the energy between the sources and the motors. In recent years, both sides have been developed as multi-agent system, which encouraged the study on energy management system (EMSs). Focusing on the EMS of the motor side, we recognized several unsolved issues.

First, almost the exiting methods do not have the capability of wheel slip prevention. The wheel-slip phenomenon results in significant energy loss, especially when the EV operates on the low friction surfaces.

Second, due to the nonlinearity and complexity of vehicle dynamics, a practical approach to system stabilization is still a challenge. Although some stability analysis methods were proposed, they require the linearization of the vehicle dynamics, and the stability condition relies on the time-varying torque distribution ratios. To alleviate the computational burden, this study aims to seek a design condition that is free from the torque distribution ratios and the linearization process.

Third, it is necessary to formulate the motor input power as a function of both torque distribution ratios and motor flux currents. This objective function has not been considered by almost all the existing methods.

1.1.2. Summary of the proposal

To deal with the aforementioned issues, this study focuses on the multi-motor EV prototype in which each wheel is driven by a permanent magnet synchronous motor (PMSM) (Fig. 1). A double-layer EMS is proposed to minimize energy consumption and guarantees safe longitudinal motion. The system has the hierarchically decentralized configuration (Fig. 2). The inner-layer distributes the torques and flux currents by minimizing the motor input power. The inner-layer also provides an aggregated speed of the motors using the torque distribution ratios. In the outer-layer, the aggregated motor speed is controlled by a disturbance observer (DOB) based controller. Based on passivity theory, a design procedure that sufficiently guarantees L2 stability of the overall system is established.

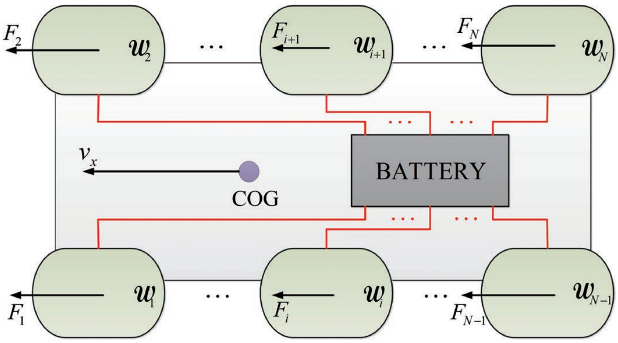


Fig. 1. Model of the multi-motor EV.

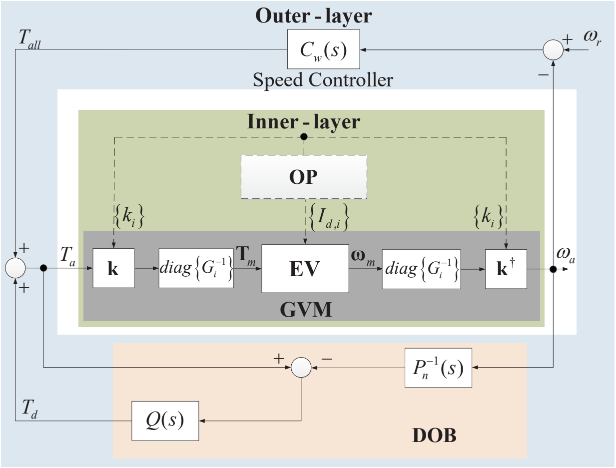


Fig. 2. Block diagram of the glocal energy management system.

The main contributions of this study can be summarized as follows (see [1], [2]):

(i) This study presents a new configuration for combining EMS with anti-slip control. The proposed configuration has only one DOB-based controller that controls the aggregated motor speed. Thanks to this configuration, the DOB control signal does not intervene the energy optimization problem. Hence, energy optimization and slip prevention algorithms can be designed independently.

(ii) This study presents a convenient and practical approach to stabilizing the overall system. Notably, the stability condition does not rely on torque distribution ratios, which are time-varying variables used to minimize the motor input power. Furthermore, there is no need to linearize the EV dynamics.

(iii) This study formulates the summation of motor output powers with copper losses and iron losses as a function of torque distribution ratios and motor flux-current. The minimization of this cost function allows instantaneous efficiency optimization in the inner-layer, together with anti-slip control in the outer-layer.

1.1.3. Main result

This study shows that, although the EV system in Fig. 1 (with N motors) is a nonlinear complex system, it possesses an important property: the passivity from the motor torque to the motor speed. Consequently, we show that the following design procedure sufficiently guarantees the L2 stability of the EMS in Fig. 2.

Design procedure of the double-layer EMS:

Stage 1-Inner-layer: Design the algorithm to minimize the summation of the input power $P_{m,i}$ with the copper loss $P_{cu,i}$ and iron loss $P_{fe,i}$.

$$\min_{\{k_i, I_{od,i}\}} \sum_{i=1}^{N} \left(P_{m,i} + P_{cu,i} + P_{fe,i} \right) \text{ s.t. } \sum_{i=1}^{N} k_i = 1,\ 0 \le k_i \le 1$$

where $\{k_i\}$ is the torque distribution ratio and $I_{od,i}$ is the motor flux current.

Stage 2-Outer-layer: Select the transfer functions $P_n(s)$, $Q(s)$, and $C_w(s)$ such that:

$F(s)$ is stable; $C_{eql}(s)$ is passive; $C_w(s)$ and $C_{equ}(s)$ are output strictly passive

$$\text{where } C_{eql}(s) = \frac{F(s)Q(s)}{P_n(s)},\ C_{equ}(s) = F(s)C_w(s),$$

$$F(s) = \frac{1}{1 - Q(s)}$$

In [1], we showed that the optimal values of the torque distribution ratios and the motor flux currents can be calculated analytically. This reduces the computational burden and enable real-time implementation of the proposed EMS.

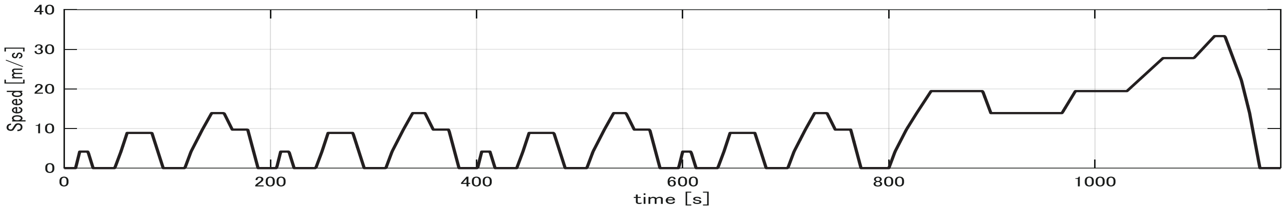
1.1.4. Evaluation of the proposal

To demonstrate the effectiveness of the double-layer EMS, this study used the 3-wheel-EV shown in Fig. 3. This EV is driven by a 13 kW PMSM connected to the rear wheel through 2 pulleys and belt. Two 4 kW axial PMSMs are directly connected to the front wheels.

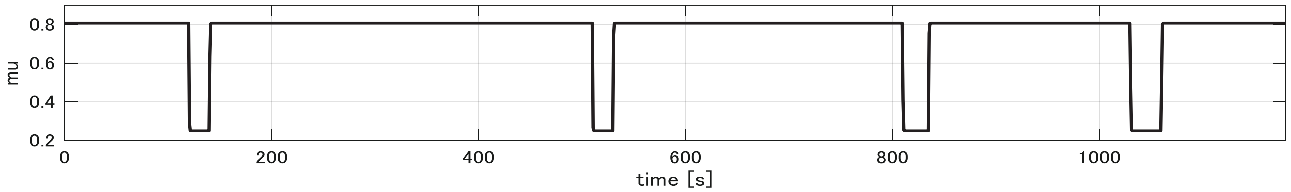
Fig. 3. Three-wheel electric vehicle.

Various tests were conducted to evaluate the proposed method. For instance, the New European Driving Cycle (NEDC) test was used to analyze the performance of the double-layer EMS with different torque and flux-current distribution strategies (Fig. 4). The NEDC's speed pattern and the change of road friction are shown in Figs. 4(a) and (b), respectively. During the NEDC, there are four periods in which the road friction changes from a high value to an exceptionally low value. The four distribution strategies are evaluated (see Table 1). The strategy S#-A (#={1, 2, 4}) maintains the motor flux current at zero value. The strategy S#-B (#={1, 2, 4}) optimizes the motor flux current by the method proposed by Morimoto *et al.* [*], and the strategy S3 utilizes the proposed algorithm.

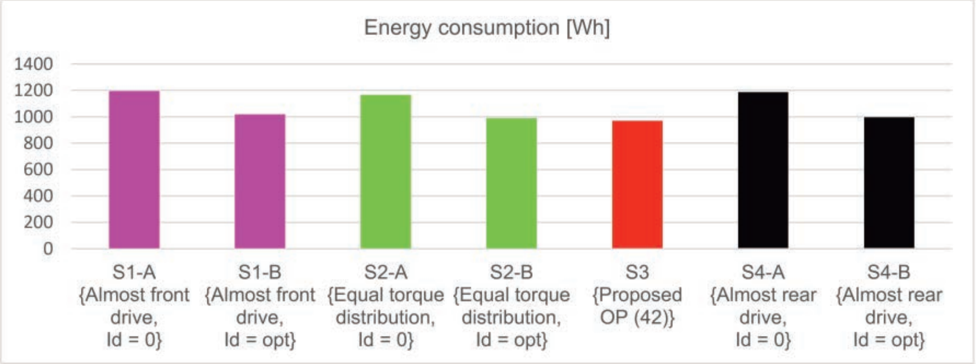
By maintaining zero flux-currents, the energy consumptions of the vehicle with S1-A, S2-A, and S4-A are 1193, 1165, and 1186 (Wh), respectively. By updating the flux-currents to minimize the power loss, the energy consumption of the vehicle with S1-B, S2-B, and S3-B are 1018, 987.3, and 996.9 (Wh), respectively. By simultaneously distributing the torques and flux-currents to minimize the input power, S3 is the best in term of energy consumption. Utilizing S3, the vehicle consumed only 969.6 (Wh). In comparison with the worst strategy of S1-A, energy consumption is reduced 18.7% by S3. The battery state of charges (SOCs) in accordance with the aforementioned strategies are illustrated in Fig. 4(d). Transparently, the SOC curves of S1-A, S2-A and S3-A are always in the lower positions in comparison with the SOC curves of S1-B, S2-B, and S4-B. Until the end of the



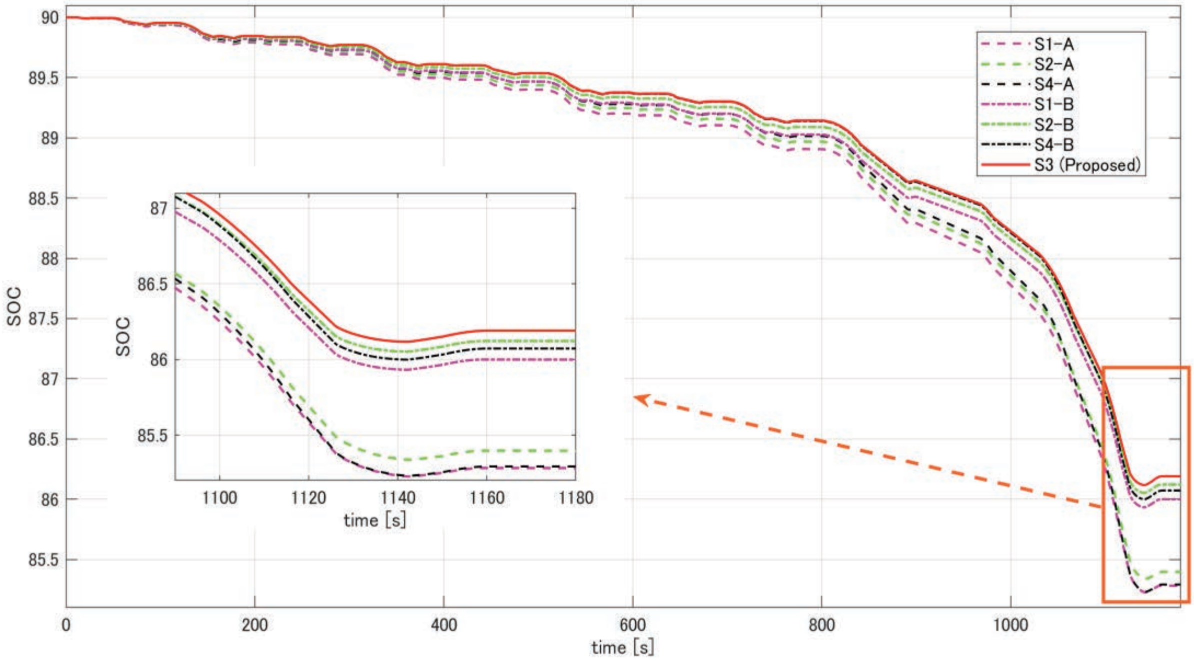
(a) Speed pattern (New European Driving Cycle).



(b) Change of road friction coefficient.



(c) Energy consumption.

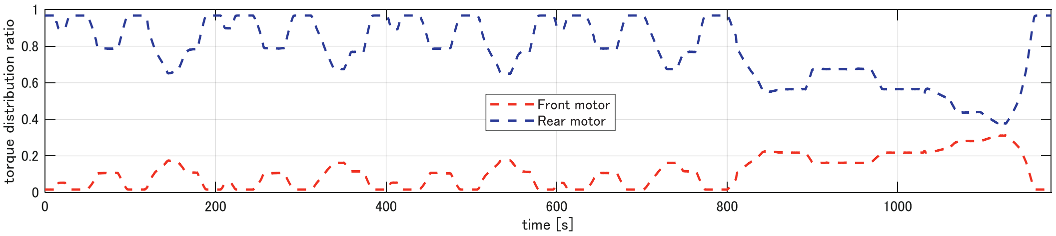


(d) Battery state of charge.

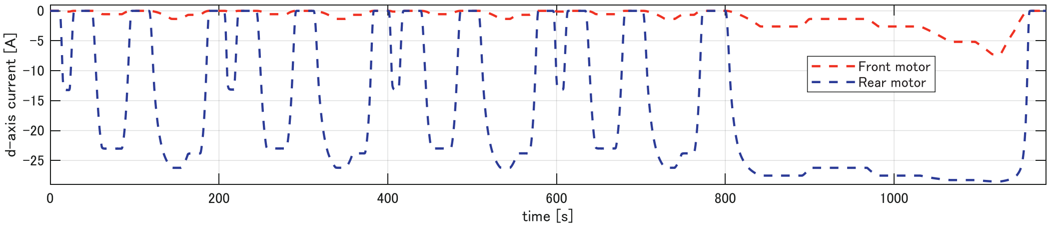
Fig. 4. Comparison of different torque and flux-current distribution strategies.

Table 1. Distribution strategies for comparison.

Strategy S1 Almost front drive		Strategy S2 Equal torque distribution		Strategy S3 The proposed OP (23)	Strategy S4 Almost rear drive	
S1-A	S1-B	S2-A	S2-B	$\{k_i, I_{d,i}\}$ is obtained by the proposed optimization algorithm.	S4-A	S4-B
$k_{1,2}=0.45$ $k_3=0.05$ $I_{d,i}=0$	$k_{1,2}=0.45$ $k_3=0.05$ $I_{d,i}=opt$	$k_{1,2}=1/3$ $k_3=1/3$ $I_{d,i}=0$	$k_{1,2}=1/3$ $k_3=1/3$ $I_{d,i}=opt$		$k_{1,2}=0.05$ $k_3=0.90$ $I_{d,i}=0$	$k_{1,2}=0.05$ $k_3=0.90$ $I_{d,i}=opt$



(a) Torque distribution ratios.



(b) Motor flux currents.

Fig. 5. Optimal torque distribution ratios and motor flux-currents given by strategy S3.

NEDC, the SOC curve of S3 always dominates the highest position. These results prove the effectiveness of the proposal. The optimal distribution ratios and flux-currents obtained by S3 are shown in Fig. 5.

[*] S. Morimoto, Y. Tong, Y. Takeda, and T. Hirasa, “Loss Minimization Control of Permanent Magnet Synchronous Motor Drives,” IEEE Transactions on Industrial Electronics, Vol. 41, No. 5, pp. 511-517, 1994.

1.2. Educational achievement

1.2.1. Master student at Toyota Technological Institute

Based on this research project, we have advised a Master student to study and successfully complete his thesis on［受動性理論に基づく電気自動車の運動制御とエネルギー最適制御の統合化］. He has obtained the knowledge on vehicle dynamics, anti-slip control, passivity theory, and the energy model of the electric motor. He presented his results at several conferences, including the 第 10 回計測自動制御学会制御部門マルチシンポジウム [3].

1.2.2. Master student at the University of Tokyo

The hierarchical decentralized control system in Fig. 2 were utilized to the longitudinal motion control in [1], [2], and [3]. Besides, we also developed the lateral dynamics version and presented it at the 2023 IEEE International Conference on Mechatronics [4]. The outer-layer is to control the yaw-rate, and the inner-layer is to control the wheel driving force via wheel speed control. We are considering the energy optimization via driving force distribution in the fiscal year 2023.

1.2.3. PhD student at University of Sherbrooke

Besides the multi-motor EV prototypes, we also considered the EV handled by multi-steering system. The idea of lateral force distribution and control via steering mechanism was presented at the 2022 IEEE Vehicle Power and Propulsion Conference [5].

1.3. Conclusions and future works

This study proposes a double-layer EMS, which can effectively utilize the electric energy by preventing the wheel slip and optimally distributing both the torque commands and the flux currents of the motors. Using a three-wheel vehicle model, we published the main finding of this study on the IEEE Transactions on Vehicular Technology [1]. The idea of hierarchical decentralized control with energy optimization has also been extended to the four-wheel independent driven formula developed at University of Sherbrooke [2].

Three students have been supported partially by this study to conduct their own research. We also organized several events to share the idea of this study to the research circles. The most successful event was the Special Session on "Advanced Control Technologies for Multi-Motor Multi-Source Vehicles" at the 2022 IEEE Vehicle Power and Propulsion Conference.

In the future, we will examine the EMS for considering both motor side and source side. With respect to the nonlinearity and complexity of the multi-motor EV system, data-driven, fuzzy logic and intelligent control algorithms can also be considered in the double-layer EMS framework. We are also looking for the practical applications of the proposed framework by collaborating with the industrial circles.

2. 発表（研究成果の発表）

2.1. Research achievement

[1] **B. -M. Nguyen**, J. P. F. Trovão, and M. C. Ta, "Double-Layer Energy Management for Multi-Motor Electric Vehicles," IEEE Transactions on Vehicular Technology, doi: 10.1109/TVT.2023.3244808 (2023).

[2] M. C. Ta, A.-T. Nguyen, **B.-M. Nguyen**, P. Messier, and J. P. F. Trovao, "Four-wheel Independently Driven Formula: Experimental EV for Motion Control Studies," 2022 IEEE Energy Conversion Congress and Exposition (2022).

2.2. Educational achievement

[3] 長谷川 大地、**B.-M. Nguyen**、川西 通裕、成清 辰生：受動性理論に基づく電気自動車の運動制御とエネルギー最適制御の統合化、第 10 回計測自動制御学会制御部門マルチシンポジウ（2023）.

[4] T. Ueno, **B.-M. Nguyen**, and H. Fujimoto, "Direct Yaw Moment Control for Electric Vehicles with Variable Rate-Slip-Ratio-Limiter Based Driving Force Control," IEEE International Conference on Mechatronics (2023).

[5] A.-T. Nguyen, **B.-M. Nguyen**, T. Vo-Duy, and M. C. Ta, "Steering Vector Control for Lateral Force Distribution of Electric Vehicles," IEEE Vehicle Power and Propulsion Conference (2022).