International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 269

A DUAL-MOTOR COUPLING PROPULSION SYSTEM SIZING AND ENERGY MANAGEMENT BASED ON BI-LEVEL PROGRAMMING METHOD

Wenwei Wang [1,2], Hong Pan[1,2*], Cheng Lin[1,2], Jiang Yi[1,2], Mingjie Zhao[1,2]

1 National Engineering Laboratory for Electric Vehicles, Beijing Institute of Technology, Beijing, 100081, China

2 Collaborative Innovation Center of Electric Vehicles in Beijing, Beijing Institute of Technology, Beijing, 100081, China

* Corresponding author

ABSTRACT

A dual-motor coupling propulsion system with multi-speed transmission offers the possibility of comprehensive improvement of the vehicle, with an increased difficulty and time cost of design though. This paper takes an electric city bus as research object to design a matching dual-motor propulsion system with two-speed transmission. For convenience and rapidity, a bi-level programming method for parameter matching and energy management of the propulsion system is established. The inner level seeks for the optimal control rules concluding gearshift schedule and torque-allocation proportion for instantaneous minimum power loss, while the outer level leverages the particle swarm optimization algorithm (PSO) to seek the optimal propulsion system parameters within reasonable limits. The objective function of the whole loop takes into account the whole power loss of the entire C-WTVC condition. It indicates that the proposed design and energy management strategy provide a significant improvement of the powertrain efficiency and great reduction of the design cost.

Keywords: Dual-motor coupling propulsion system, Parameter matching, Energy management optimization, bi-level programming

1. INTRODUCTION

The traditional single motor automated mechanical transmission system has limited potential in terms of improving the comprehensive performance of an electric bus. While dual-motor coupling propulsion (DMCP) systems have powerful dynamic performance and huge room for energy optimization from design to control. For parameters matching design, most of the existing methods used by engineer are based on the vehicle's dynamic performance, mainly for centralized single-motor driven vehicles. For example, the peak power of the power system is determined by the vehicle's maximum speed and maximum grade. However, the actual system parameters are strongly coupled with each other and control strategy. It is easy to cause improper selection of parameters and waste of energy when the above method is utilized alone, especially for the more complicated DMCP. Therefore, some scholars take vehicle energy consumption as the optimization target of parameters design. Zhang LP et al took predetermined functions and actual demands of different operating statuses as optimization target to match the system parameters for improving the economy [1,2]. And the bi-level optimization algorithm is the most commonly used method to solve the coupling parameters and control strategy optimization. Hu X et al. [3] established a fast optimization method based on convex programming for multi-power source coupling problem. However, there is no shifting mechanism in its drive system and its applicability with discrete parameters needs to be verified. In addition, some intelligent algorithms such as quantum genetic algorithm and simulated annealing particle swarm optimization algorithm are also used to reduce the time cost of optimization [4]. As for control strategy, rule-based control strategy has been widely used to handle energy management problems with robust property and fast calculation [5]. However, it can hardly obtain the optimal energy consumption performance, leading other algorithms such as dynamic programming and model predictive control, to performence with better economy [6].

In this paper, a dual-motor coupling propulsion is designed from parameters matching to control strategy optimization by bi-level programming. In section 2, the system model is built and the mode switching principal is introduced. in section 3, the structure and process of bi-level programming process are given. The simulation results are illustrated, compared and discussed in Section 4 before conclusions drawn in the final section.

2. DUAL-MOTOR PROPULSION SYSTEM MODELING

The dual-motor propulsion system(DMPS) studied in this paper is a centralized drive system, as shown in Fig. 1. Here an auxiliary motor (AM) equipped with a two-speed planetary transmission and a traction motor (TM) connected directly to the rear axle can drive the vehicle in a torque-coupling way.

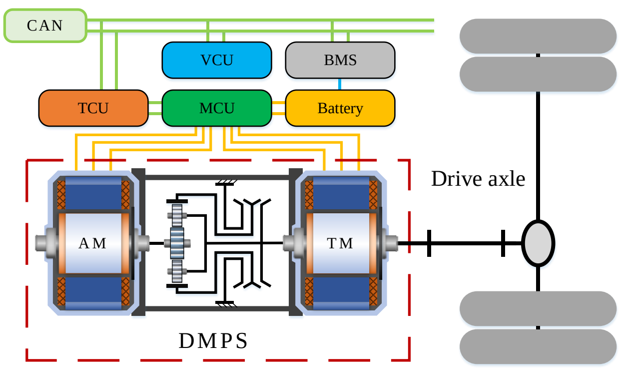


Fig. 1. Configuration of the dual-motor coupling propulsion system

Modeling of the propulsion system is based on the key specifications of the target electric bus, as shown in table 1. And it should be pointed out that we have already made a prototype system before this work, of which the parameters are set as the baseline, concluding the sizes of two identical motors and the transmission, as shown in table 2.

The system model involves the model of the motors, the planetary transmission and vehicle dynamics. The battery model is not needed since there is only one single power source and we assume no mode switching loss or torque-variation loss between two moments.

Table 1 Key specifications of the electric bus

Item	Value
Maximum Design Total Mass (m) / kg	16000
Vehicle Frontal Area (A_W) / m^2	8.125
Wheel Rolling Radius (r) / m	0.5065
Correction Coefficient of Rotating Mass (δ)	1.08
Coefficient of Wind Resistance (C_D)	0.65
Coefficient of Rolling Resistance (f)	0.01
Rear Axle Ratio (i_0)	5.125
Rear Axle Efficiency (η_0)	0.9

Table 2 Baseline parameters of the propulsion system

Item	Value
Motor Peak Power ($P_{TM,Peak,base}$, $P_{AM,Peak,base}$) / kW	150
Motor Maximum Speed ($n_{TM,MAX}$, $n_{AM,MAX}$) / rpm	4500
Motor Peak Torque ($T_{TM,Peak,base}$, $T_{AM,Peak,base}$) / Nm	1100
Transmission Gear Ratio (i_{g1}, i_{g2})	3, 1
Transmission Efficiency at Gear 1 (η_{g1})	0.96
Transmission Efficiency at Gear 2 (η_{g2})	0.98

2.1 Motor Model

Only the drive situation is introduced here since the braking process is basically the same as the driving process. The motor model is based on the efficiency map of the prototype motor, as shown in Fig. 2, obtained through the bench test. Thus a quadratic function is leveraged to fit the power losses of motor relative to the output torque as follows:

$$P_{loss} = aT_{motor}^{\ 2} + bT_{motor} + c \tag{1}$$

where a, b, c are functions of the motor speed n.

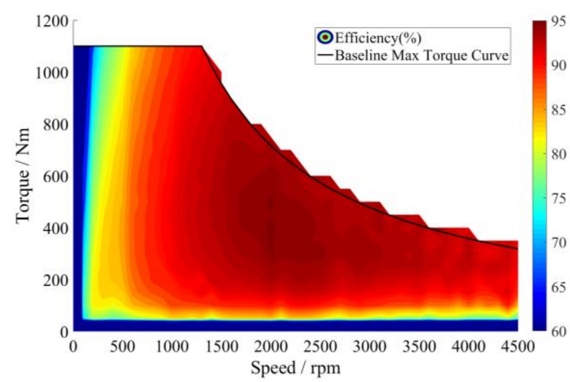


Fig. 2. Motor drive efficiency MAP

To resize TM/AM, we define s as the size coefficients of dual motors. The torque range and power loss of the new motor are assumed to be proportional to the baseline ones respectively, which can be expressed as follows:

$$\begin{cases} 0 \le T_{motor} < sT_{MAX,base}(n) \\ P_{loss} = sP_{loss,base} \end{cases} \tag{2}$$

where $T_{MAX,base}(n)$ is the baseline max torque curve.

By merging formula (1) and (2), the power loss of the resized motor can be expressed as:

$$\begin{aligned} P_{loss} &= sP_{loss,base} \\ &= s(aT_{base}{}^2 + bT_{base} + c) \\ &= s\left[a\left(\frac{T_{motor}}{s}\right)^2 + b\frac{T_{motor}}{s} + c\right] \\ &= a\frac{T_{motor}{}^2}{s} + bT_{motor} + cs \end{aligned} \tag{3}$$

2.2 Transmission Model

Here a simplified empirical model is utilized to simulate the working states of the planetary transmission, with constant mechanical efficiencies at each gear. A variable $e_{t,gi}$ is defined to depict the different working modes of the transmission at. The output coupling torque of the propulsion system can be expressed with e_t:

$$T_{dem} = T_{TM} + e_{t,gi} i_{gi} T_{AM} \eta_{gi} \tag{4}$$

and $e_{t,gi}$ is determined by whether the system output torque demand T_{dem} is less than the threshold $T_{threshold,gi}$:

$$e_{t,gi} = \begin{cases} 0 & T_{dem} \le T_{threshold,gi} \\ 1 & T_{dem} > T_{threshold,gi} \end{cases} \tag{5}$$

where $T_{threshold,gi}$ is one of the variable to be optimize. Namely, T_{dem} decides whether the AM contribute to driving the vehicle.

Then The power loss of the transmission engaged can be expressed as:

$$P_{loss,transmission,gi} = e_{t,gi}\frac{n_{AM}(T_{dem} - T_{TM})}{9550 i_{gi} \eta_{gi}} \tag{6}$$

2.3 Vehicle Dynamic

The propulsion system must output enough power to overcome the driving resistance of vehicle on the road. The driving resistance at moment *k* of the condition is calculated from the vehicle longitude dynamic as follows:

$$\begin{aligned} T_r(k) &= mg\sin\alpha(k) + fmg\cos\alpha(k) \\ &+ \frac{C_D A_W v(k)^2}{21.15} + \delta m a(k) \end{aligned} \tag{7}$$

and due to the rear axle mechanical loss, considering the entire driveline, the demand output torque of the propulsion system wheel should be:

$$T_{dem}(k) = \frac{T_r(k) r}{i_0 \eta_0} \tag{8}$$

3. BI-LEVEL PROGRAMMING OPTIMIZATION

The bi-level programming optimization consists of the inner level of the torque allocation and gear shift control based on the minimum power loss of the propulsion system at moment *k*, and the outer level determines the optimal motor size coefficients *s* and the torque threshold $T_{threshold,gi}$ according to the whole power loss during the driving condition. The bi-level structure is as depicted in Fig. 3.

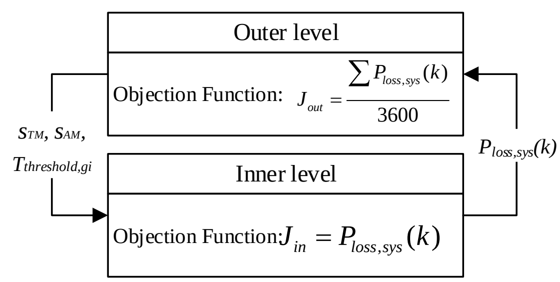


Fig. 3. Bi-level structure

3.1 Outer level programming

The optimization variables of this level are s_{TM}, s_{AM}, $T_{threshold,g1}$ and $T_{threshold,g2}$. s_{g1} and s_{g2} are utilized to limit the $T_{threshold,gi}$ in a possible range as:

$$T_{threshold,gi} = s_{gi} T_{MAX} \tag{9}$$

where s_{gi} ranges from 0 to 1. And in order to ensure that the cost of the whole propulsion system is unchanged, we assume that the total peak power and torque of TM and AM keep constants, which means

$$s_{TM} + s_{AM} = 2 \tag{10}$$

At the same time, s_{AM} is set to range from 0 to 1, to limit that the AM is smaller than the TM, in line with the principle that AM is a power supplement to TM.

The objective function of this level is the total system power loss of the whole condition, as:

$$J_{out} = W_{loss} = \frac{\sum P_{loss,sys}(k)}{3600} \tag{11}$$

where the system power loss $P_{loss,sys}(k)$ is exactly the objective function of the inner level.

In this paper, the Particle Swarm Optimization(PSO) algorithm is utilized to seek for the optimal s_{AM} (while s_{TM} can be obtained by formula (10)), s_{g1} and s_{g2} since there are discrete variables existing in the objective function, such as $e_{t,gi}(k)$ and the gear $g(k)$, making it a non-convex problem, which will be introduced in the inner level. And the detail parameters of the PSO algorithm we adopt is as shown in table 3.

Table 3 Parameters of the PSO algorithm

Item	Specification
Fitness Function	$J_{out} = W_{loss}$
Number of Particles(N)	50
Acceleration Constant1(c_1)	2
acceleration Constant2(c_2)	2
Inertia Weight(w)	0.5
Max Iterations Times(M)	500
Input Dimension(D)	3
Optimal Position(x_{op})	$[s_{AM,OP} \quad s_{g1,OP} \quad s_{g2,OP}]$
Optimal Fitness Function	$J_{out,OP}$

The initial position and velocity of the particles are set to be random between 0 and 1 and updated by expression as follows:

$$\begin{cases} v_{i,j}(t+1) = wv_{i,j}(t) + c_1 r_1 [p_{i,j} - x_{i,j}(t)] \\ +c_2 r_2 [p_{g,j} - x_{i,j}(t)] \\ x_{i,j}(t+1) = x_{i,j}(t) + v_{i,j}(t+1) \end{cases} \tag{12}$$
$$i = 1,2 \ldots N,\ j = 1,2 \ldots D, t = 1,2 \ldots M$$

where r_1 and r_2 are random number between 0 and 1, and $p_{i,j}$ is the optimal solution of each particle itself while $p_{g,j}$ is the optimal solution of all of the whole swarm.

3.2 Inner level programming

The inner lever is concentrated on the system control strategy at single moment k. The optimization variables conclude $T_{TM}(k)$, $T_{AM}(k)$ and the gear $g(k)$.

The objective function of this level is system power loss $P_{loss,sys}(k)$, which is sum of components' power loss:

$$J_{in} = P_{loss,sys}(k) = P_{loss,TM}(k) + P_{loss,AM}(k) + P_{loss,transmission,gi} \tag{13}$$

where $P_{loss,TM}$ and $P_{loss,AM}$ can be calculated from formula (4) ~ (5), as:

$$P_{loss,TM}(k) = a_{TM}(k)\frac{T_{TM}(k)^2}{s_{TM}} + b_{TM}(k)T_{TM}(k) + c_{TM}(k)s_{TM} \tag{14}$$

$$\begin{aligned} P_{loss,TM}(k) &= e_{t,gi}(k)[a_{AM}(k)\frac{T_{AM}(k)^2}{s_{AM}} + b_{AM}(k)T_{AM}(k) + c_{AM}(k)s_{AM}] \\ &= e_{t,gi}(k)[a_{AM}(k)\frac{(\frac{T_{dem}(k) - T_{TM}(k)}{i_{gi}(k)\eta_{gi}(k)})^2}{s_{AM}} + b_{AM}(\frac{T_{dem}(k) - T_{TM}(k)}{i_{gi}(k)\eta_{gi}(k)}) + c_{AM}(k)s_{AM}] \end{aligned} \tag{15}$$

and $P_{loss,transmission,gi}$ from formula (6).

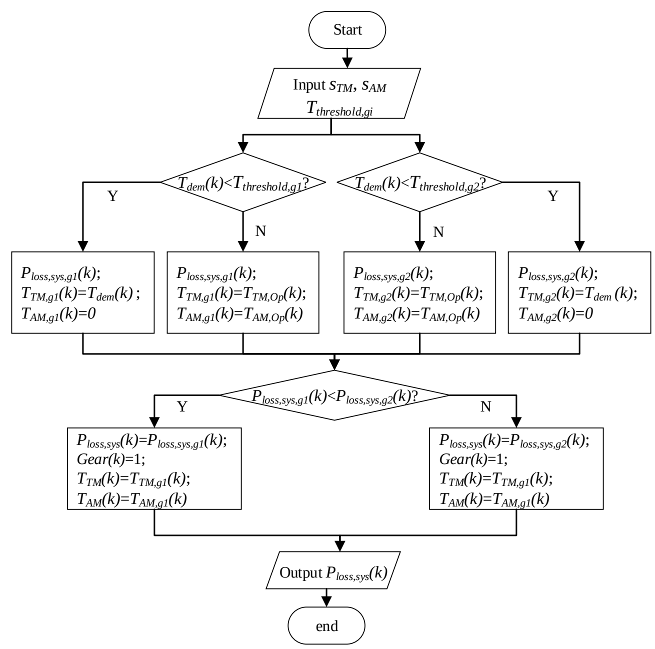


Fig. 4. Logic flowchart of inner level

By receiving the motor size value and $T_{threshold,gi}$ determined by the outer level, the inner level can get $e_{t,gi}$ through formula (5). Though the entire $P_{loss,sys}(k)$ is not a convex function, the $P_{loss,sys}(k)$ can be finally expressed as a quadratic function of $T_{TM}(k)$ at gear gi as:

$$P_{loss,sys,gi}(k) = a_{sys,gi}(k)T_{TM}(k)^2 + b_{sys,gi}(k)T_{TM}(k) + c_{sys,gi}(k) \tag{16}$$

which is obviously a convex problem and easy to get the minimum $P_{loss,sys,gi}(k)$ and corresponding $T_{TM}(k)$ at each gear by calculation.

Finally the optimal gear $g_{op}(k)$, power loss $P_{loss,sys,op}(k)$ and output torque of TM $T_{TM}(k)$ at moment k can be decided by comparing $P_{loss,sys,g1}(k)$ and $P_{loss,sys,g2}(k)$. The logic flowchart of the inner level is shown as Fig. 4.

4. RESULTS AND DISCUSSION

We take CWTVC as the simulated condition to run the bi-level programming, of which the vehicle velocity curve is shown as Fig. 5. The outcomes of the outer PSO level is shown in table 4, concluding the optimal sizes of dual motor and the torque thresholds determining whether the AM is engaged in working. The minimum power loss is obtained when $P_{TM,Peak}$ is 195.09 kW and $P_{AM,Peak}$ is 104.91 kW, $T_{TM,Peak}$ is 1430.66 Nm and $T_{AM,Peak}$ is 769.34 Nm. The torque threshold results are more significant, since the optimal $T_{threshold,g1}$ is 447.51 Nm under which the vehicle is only driven by TM when the torque is demanded. And, specially, the optimal $T_{threshold,g2}$ is 1386.88 Nm, extremely close to its peak torque, which means TM should always work preferentially alone until the T_{dem} reach close t its torque limit.

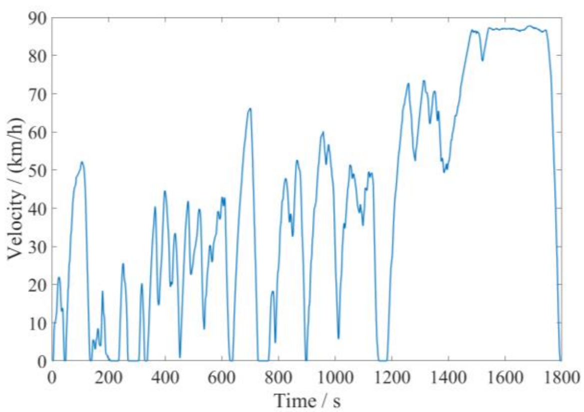


Fig. 5. Velocity curve of CWTVC

Table 4 Results of optimal motor sizes and torque thresholds

Item	Result
$J_{out,OP}$ / kWh	1.5299
$s_{TM,OP}$	1.3006
$s_{AM,OP}$	0.6994
$s_{g1,OP}$	0.3128
$s_{g2,OP}$	0.9694
$P_{TM,Peak}$ / kW	195.09
$P_{AM,Peak}$ / kW	104.91
$T_{TM,Peak}$ / Nm	1430.66
$T_{AM,Peak}$ / Nm	769.34
$T_{threshold,g1}$ / Nm	447.51
$T_{threshold,g2}$ / Nm	1386.88

Compared to the initial identical motors with $T_{threshold,gi}$ equal the motor rated torque 600Nm, the propulsion system power loss of whole CWTVC decreased by 24.2 %, from 2.0173 kWh to 1.5299 kWh, which is more intuitive in the inner level results of torque allocation and gear shift control. The dual motors operating points of the initial motors and control strategy is as shown in Fig. 7 and the optimal one's in Fig. 8. It can be seen that the motor operating points of the optimal scheme are significantly more distributed in the high efficiency area, especially for TM's in the black dotted box. And less AM operating points are distributed in low efficiency area which can be seen in the white dotted box.

And it is notable that the optimal result of particle swarm optimization converges rapidly with a time cost of 39.279 s to reach a very stable state in 500 iterations as shown in Fig. 8, which proves the efficiency and robustness of this method.

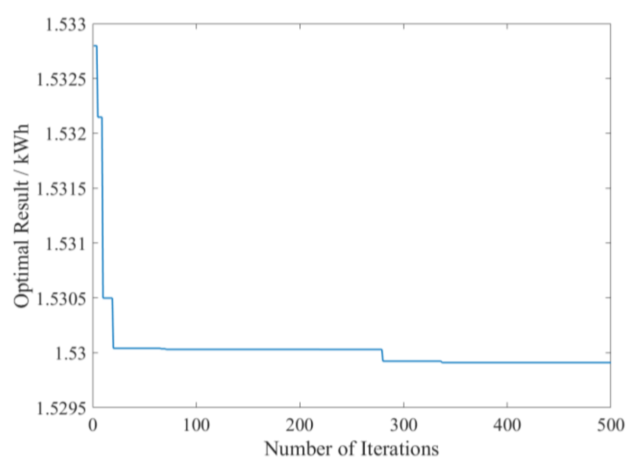
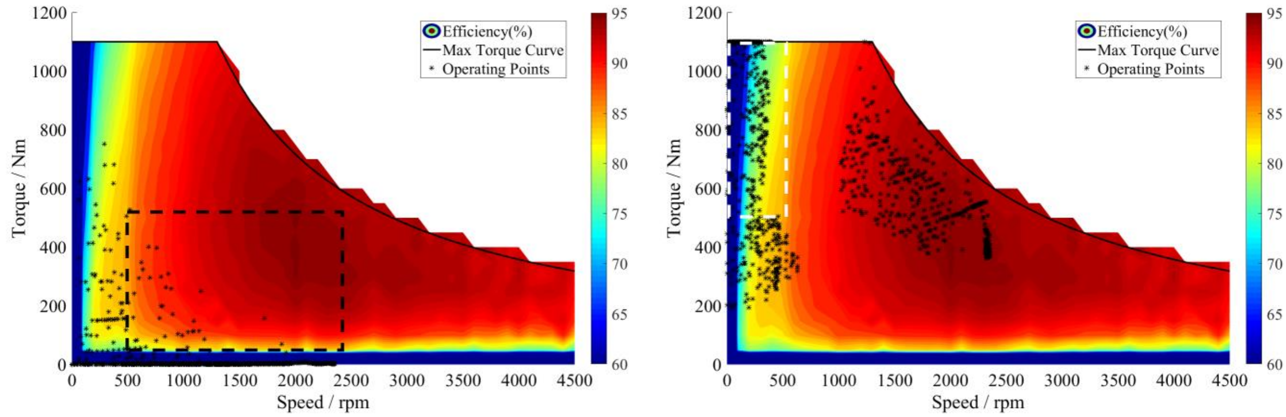


Fig. 6. Optimal result iterations curve

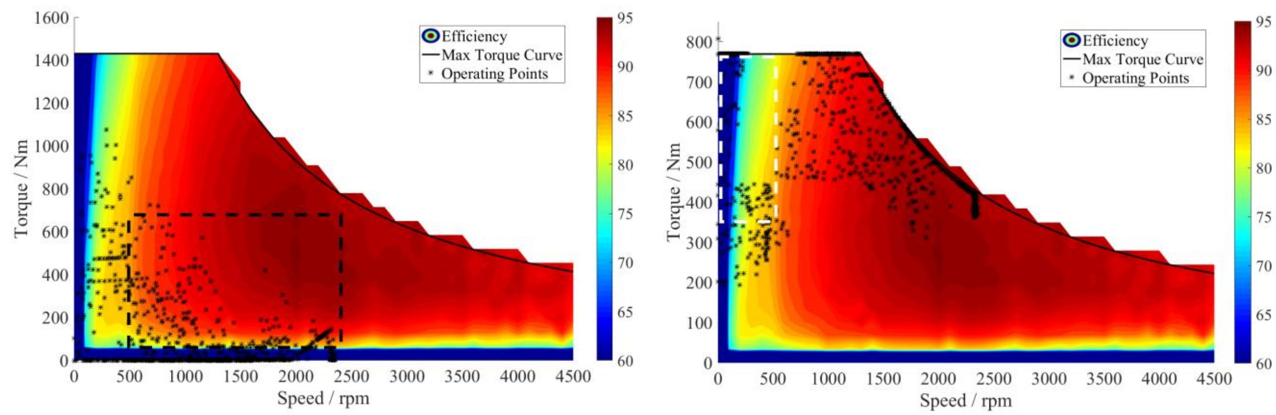
5. CONCLUSIONS

An electric bus dual-motor coupling propulsion system is re-designed for both its motor sizes and energy management concluding torque allocation and gear shift



(a)TM (b)AM

Fig 7 Motor operating points of initial baseline motors



(a)TM (b)AM

Fig 8 Motor operating points of optimal scheme's motors

control strategy. An effective and robust bi-level programming method is formulated to seek for the optimal results and it shows that:

1) The suggested optimal sizes and strategies obtained from bi-level programming can significantly reduce the propulsion system power loss. For CWTVC, the power loss decreases by 24.2%.

2) The bi-level programming method is proved to be both rapid and robust that the result converges in 39.279s and reach a stable state within 500 iterations.

ACKNOWLEDGEMENT

This work was supported by the National Key Technology Research and Development Program of China (2017YFB0103801). Any opinions expressed in this paper are solely those of the authors and do not represent those of the sponsors.

REFERENCE

[1] Zhang LP, Li L, Qi BN, et al. Parameters optimum matching of pure electric vehicle dual-mode coupling drive system[J]. SCI CHINA TECHNOL SC, 2014, 57:2265-2277

[2] Zhang S, Xiong R, Zhang C. Pontryagin's Minimum Principle-based power management of a dual-motor-driven electric bus[J]. APPL ENERG, 2015, 159:370-380

[3] Hu X , Li Y , Lv C , et al. Optimal Energy Management and Sizing of a Dual Motor-Driven Electric Powertrain[J]. IEEE Transactions on Power Electronics, PP(99):1-1

[4] Wang Y, Sun D. Powertrain Matching and Optimization of Dual-Motor Hybrid Driving System for Electric Vehicle Based on Quantum Genetic Intelligent Algorithm[J]. Dyn. Nat. Soc. 2014, 2014, 956521

[5] H. B, S. A, Y. C. A rule-based energy management strategy for Plug-in Hybrid Electric Vehicle (PHEV): 2009 American Control Conference, 2009[C].2009 10-12 June 2009

[6] Zhao M, Shi J, Lin C, et al. Application-Oriented Optimal Shift Schedule Extraction for a Dual-Motor Electric Bus with Automated Manual Transmission[J]. ENERGIES, 2018, 11(2):325