Design and Simulation of an Extended-Range Dynamic System for an Amphibious Vehicle

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Abstract. Taking the crawler amphibious vehicle as the research object, the dynamic system is designed with an extended-range structure. Based on the design parameters and performance indicators, the vehicle dynamics is used to calculate the power demand and torque demand of the dynamic system that meets the design conditions, and then the power component selection and matching calculation. Based on the CRUISE vehicle simulation software, the vehicle model of the extended-range structure is established. Design a constant temperature control strategy and the cycle run simulation and performance indicators verification are set. The designed extended-range dynamic system meets the design indicators, and the vehicle has powerful performance and meets the driving mileage requirements. Lay the foundation for subsequent laboratory bench testing.

1. Introduction

The amphibious vehicle has the advantages of being able to pass through both water and land, and has a wide application value, which has attracted people's attention. In the military field, amphibious vehicles can quickly pass through the shoal from the landing ship to reduce the casualties of the soldiers, or used in the inland water network zone; in the civilian field, rapid maneuvering can be achieved on the muddy road when the flood occurs. If an amphibious vehicle only uses a fuel engine as a power source, it will be limited because it cannot meet the noise requirements in specific occasions and increasingly strict emission requirements. The use of an electric motor as a power source is subject to battery performance and cannot guarantee the cruising range; and if the silent driving power is all provided by the generator, the generator's power and volume will be very large, adding more weight.

In order to solve the problem of high noise and high emissions, and to increase driving range and reduce the weight of the whole vehicle, this paper uses an extended-range dynamic system. The extended-range vehicle is similar to an electric vehicle. The main power comes from the battery pack. The difference is that the extended-range vehicle adds a range-extender composed of the engine and the generator, and is connected in parallel with the battery to provide power for the vehicle. When the remaining battery power is consumed to the lower limit, the range-extender starts to charge the battery to meet the driving demand [1]. The extended-range dynamic system can meet the requirements of silence and long driving distance at the same time, thus having obvious advantages.

The design of the power system is the key content of the extended-range amphibious vehicle. Only the reasonable calculation and selection of of the power system components' parameters can fully guarantee the performance of the vehicle. At present, there is no research on the application of distributed drives in extended-range vehicles, mostly centralized drives. There are many advantages to applying the in-wheel-motor to the amphibious vehicle, such as: saving the space inside the vehicle and conveniently arranging other components; compared with the mechanical transmission, the timeliness of the electric drive is better; the in-wheel-motor can be independently controlled, which can realize the pivot steering.

This paper takes the amphibious crawler vehicle as the research object. Firstly, it introduces the overall scheme of the extended-range amphibious vehicle dynamic system. Then the vehicle's design parameters and performance indicators are proposed. After calculating the required power and torque through the vehicle dynamics, select and match the power components. Finally, based on the vehicle simulation software CRUISE, the vehicle model of the extended-range structure is established. The constant temperature control strategy designed by Simulink is used to realize the joint simulation, and the cycle condition simulation and performance index verification are set.

2. The overall plan of the extended-range amphibious vehicle's dynamic system

The structure of the extended-range system proposed in this paper is shown in Figure 1. It consists of in-wheel-motor, a power battery pack, a water jet propeller, a vehicle control unit, a gearbox, a motor drive control system and a range-extender. The vehicle control unit is connected to the engine, the gearbox and the power battery pack, and the motor drive control system is connected via the CAN bus to realize the vehicle control. The engine is connected to the gearbox through a solid shaft. Then the power is transferred to the water jet propeller. The generator/motor is a secondary component designed as a hollow structure that fits over the solid shaft. The two clutches M, N are used to indicate the on and off state of the energy's transfer. On the water surface, M and N are closed, and the engine directly drives the water jet propeller. On land, when the battery pack's energy is sufficient, it supplies power to the in-wheel-motor through the motor drive control system; when the battery pack's energy is insufficient, M and N are disconnected, the secondary component works in the electric state to drive the engine to start. After the engine reaches the predetermined speed, the secondary component works in the generation state. At this time, the engine drives the generator, and the output electrical power drives the wheel motor, and the excess power supplies the power battery. Throughout the process, the engine is isolated from the outside environment and does not drive the vehicle directly. So the engine can work in an efficient area.
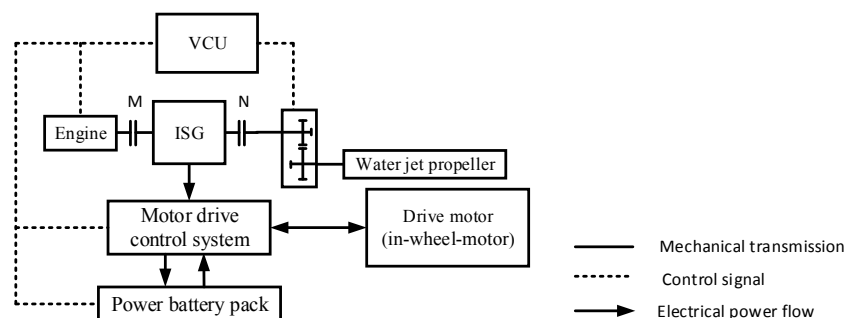
Figure 1. The structure of the extended-range amphibious vehicle's dynamic system.

3. Matching design of dynamic system parameters for extended-range amphibious vehicles

The parameters' matching idea is to calculate the power demand and torque demand of the power system that meets the design conditions through the vehicle dynamics, and then carry on the power components' selection and matching. The power components are mainly drive components (here referred to as the in-wheel-motor), the range-extender (the engine and the generator), the power

battery pack and the fuel tank. The system needs to be simplified before the parameters are matched to facilitate analysis. The amphibious crawler vehicle is a relatively complex nonlinear system. It is assumed that the vehicle's load distribution is uniform, and the vertical load on both sides of the track is equal, and the ground resistance coefficient is constant, excluding the impact of slip [2].

3.1. Vehicle's parameters and design indicators
The vehicle parameters and design indicators are shown in Table 1.

Table 1. Vehicle parameters and design indicators.

Parameter	Value	Parameter	Value
Driving wheel radius / mm	200	Maximum mileage on water / km	≥25
Curb weight / kg	2100	Maximum speed on land / (km/h)	≥55
Total mass / kg	2900	Maximum speed on water / (km/h)	≥20
Windward area / m^2	3.2	Off-road average speed / (km/h)	≥18
Maximum road mileage / km	≥90	Maximum slope angle / (°)	≥18
Pure electric mileage / km	≥8		

3.2. In –wheel-motor's parameters design
The selection condition of the in-wheel-motor is to select the motor with lower rated power under the premise of ensuring the demand of torque, speed and power, so as to avoid the motor aging and the life when it is not running under the rated condition. The amphibious vehicle is always affected by rolling resistance and air resistance. It is also affected by the climbing resistance during the climbing condition and the inertia force under the acceleration and deceleration conditions. Considered of all the driving forces, the equation of the amphibious vehicle can be listed as follows:

$$F = F_f + F_i + F_w + F_j = fmg\cos\beta + mg\sin\beta + \frac{C_w A \rho_A v^2}{2} + \delta m \dot{v} \tag{1}$$

$$F = \frac{3600P}{v} \tag{2}$$

Where F is the driving force of the whole vehicle; m is the total mass of the vehicle; v is the vehicle's speed; C_w is the air resistance coefficient, taking 0.65; β is the maximum slope angle; ρ_A is the air density, taking 1.225 kg/m^3; δ is the mass increase factor, caused by rotating parts in the vehicle; g is the gravity acceleration, taking 9.81 m/s^2 under standard atmospheric pressure; f is the rolling drag coefficient, refered to the reference [3], selecting 0.05 at pavement and 0.3 at cross country road.

The peak power of the in-wheel-motor is determined by the maximum value of the peak power under 3 typical operating conditions.

1) The pavement is passed with a maximum speed of v_1=55 km/h, and the rolling resistance coefficient f_1 is taken as 0.05. By ignoring the uphill resistance and the acceleration resistance, equations (1) and (2) can be simplified as:

$$\frac{3600P_1}{v_1} = f_1 mg + \frac{C_w A \rho_A v_1^2}{2} \tag{3}$$

The four in-wheel-motor are driven by the speed reducer after the torque reduction, and each in-wheel-motor provides power:

$$P_{dj1} = \frac{P_{j1}}{4} = \frac{P_1}{4\eta_T} \tag{4}$$

Where η_T is the transmission system efficiency, which is the ratio of the power required to drive the vehicle to the power of the 4 in-wheel-motor, taking 0.75; P_{j1} is total power of the in-wheel-motor.

Combined with equations (3) and (4), P_{dj1} is calculated to be 8.734 kW.

The speed of the in-wheel-motor is:

$$n_1 = \frac{v_1}{2\pi r} = 729.46 \ \text{r/min} \tag{5}$$

The torque of each in-wheel-motor is:

$$T_{dj1} = \frac{9550 P_{dj1}}{n_1} = 114.34 \ \text{Nm} \tag{6}$$

2) Climb the 18° slope at a constant speed of v_2=5 km/h, and take the rolling resistance coefficient f_2 as 0.2. Ignoring the acceleration resistance and air resistance, the equations (1) and (2) can be simplified as:

$$\frac{3600 P_2}{v_2} = f_2 m g \cos \beta + m g \sin \beta \tag{7}$$

The calculation of the rotational speed and torque of the in-wheel-motor is the same as (5) and (6). It can be calculated as: P_{dj2}=6.58 kW, n_2=66.3 r/min, T_{dj2}=946.9 Nm.

3) Pass the off-road road at a maximum speed of v_3=18 km/h, and the rolling resistance coefficient f_3 is taken as 0.3. Ignoring the acceleration resistance and the slope resistance, the equations (1) and (2) can be simplified as:

$$\frac{3600 P_3}{v_3} = f_3 m g + \frac{C_w A \rho_A v_3^2}{2} \tag{8}$$

The calculation of the rotational speed and torque of the in-wheel-motor is the same as (5) and (6). It can be calculated as: P_{dj3}=14.28 kW, n_3=238.7 r/min, T_{dj3}= 571.1 Nm.

In combination with the above 3 typical operating conditions, the requirements for a single in-wheel-motor are a maximum power of 14.28 kW, a maximum torque of 946.9 Nm, and a maximum speed of 729.46 r/min. Taking a safety factor of 1.1 ensures a design margin. Select the in-wheel-motor parameters as shown in Table 2. The in-wheel-motor reduction ratio of 6.2 can meet the above requirements.

After selecting the in-wheel-motor, the theoretical maximum speed that can be achieved by the amphibious vehicle can be calculated as 75 km/h.

Table 2. In-wheel-motor assembly parameters.

Parameter	Demand	Including design margin	Assembly parameter
Peak power / kW	14.28	15.71	35
Peak torque / Nm	946.9	1041.6	1300
Maximum speed / (r/min)	729.46	802.41	1000

3.3. Range-extender's parameters design

3.3.1. Generator's parameters design. The generator is driven by the engine to charge the battery or to drive the in-wheel-motor directly. The generator's selection requirement is a large speed range, which can cover the engine speed range; the volume is small, and the interior space of the vehicle can be arranged conveniently; the power can be instantaneously output. The choice of permanent magnet synchronous motor can meet the above requirements.

According to the "2.2 In-wheel-motor parameters", the maximum power P_{j3} of the amphibious vehicle in the onshore working condition is 57.11 kW. Considering the power consumption of other components as 10 kW and the design margin, choose the the generator whose rated power is 90 kW

and peak power is 130 kW. So it can meet the requirements. Other parameters of the generator are shown in Table 3.

Table 3. Some of generator's parameters.

Parameter	Value	Parameter	Value
Rated torque / Nm	340	Rated speed / (r / min)	2400
Peak torque / Nm	750	Peak speed / (r / min)	6200
Rated voltage / V	330	Cooling method	Water cooling

3.3.2. Engine's parameters design. Amphibious vehicles require much more power on water surface than on land. The engine output power is adjusted via the gearbox to drive the water jet propeller. The vehicle body model is carried out by using 3D software, then it is used in the fluid software for drag simulation, and the field drag model is used to obtain the fluid resistance and driving power of the amphibious vehicle. Therefore, the selection results of the cooperative company are used directly, and some parameters of the engine which is selected are shown in Table 4:

Table 4. Some of engine parameters.

Parameter	Value
Displacement / L	3
Rated power / kW	210
Maximum torque / Nm	600

According to the power required by the onshore working conditions, and matched with the water jet propulsion device, the power state curve of engine working on the water surface can cover the power curve required by the water jet propulsion device through the transmission ratio adjustment. In order to ensure the power and speed required for water and land conditions, the engine is set to two working conditions: the ground working speed is set at 850~2500 r/min, and the water working condition is 2100~4200 r/min. The match of the range extender is mainly the speed matching between the engine and the generator. The rated speed of the generator is 2400 r/min and the peak speed is 6200 r/min, which can match the engine speed well.

3.3.3. Water mileage check. The tank capacity designed is 80 L. The water mileage check is as follows:
The water working conditions are set to a maximum speed of 20 km/h and a vehicle power of 210 kW. Select the point B in Figure 2 as the driving condition point. The engine speed is 4000 r/min, and the fuel consumption rate is 250 g/kWh.
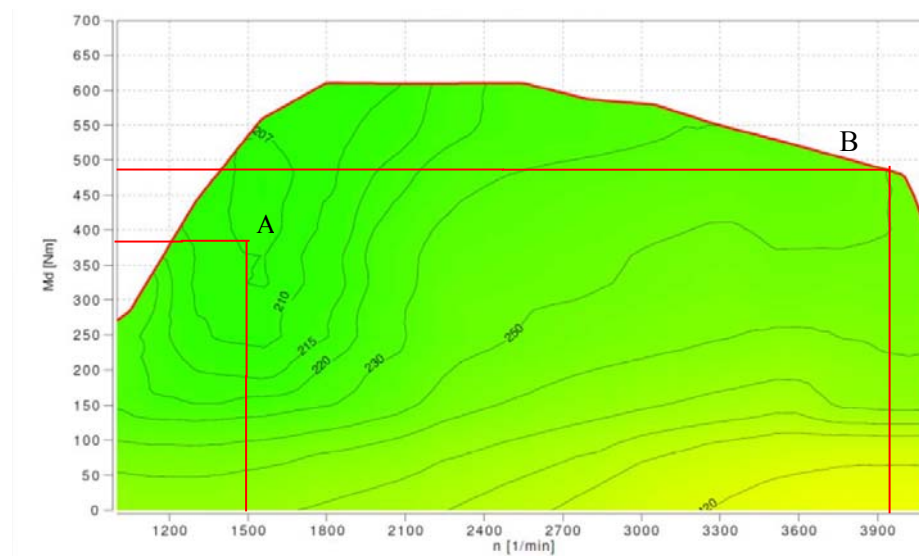
Figure 2. Engine fuel consumption curve.

The maximum driving range equation is:

$$S = \frac{V \rho v}{P_e k} \times 10^3 \qquad (9)$$

Where S is maximum driving range; V is the effective volume of the fuel tank; P_e is the engine power; ρ is the fuel density, taking 0.84 kg/L; v is the driving speed; k is the fuel consumption rate. Find S = 25.6 km, which meets the water mileage requirements.

The onshore conditions are set to a maximum speed of 55 km/h. Select point A in Figure 2 as the operating point, engine speed 1500 r/min, torque 382 Nm, the engine power 60 kW, the fuel consumption rate 207 g/kWh. Since the engine does not directly drive the wheels under land conditions, the above method cannot be used for the mileage check of the land conditions. In the following text, software simulation analysis is used to obtain the driving range of land conditions.

3.4. Battery pack's parameters design

The parameters' design of the power battery pack needs to consider two aspects: one is high power density, which can charge and discharge with a large current; the other is to meet the requirements of silent driving mileage. Comparative analysis of 3 kinds of commonly used batteries: lead-acid batteries, nickel-metal hydride batteries, lithium-ion batteries, amphibious vehicle's batteries are selected as ternary lithium batteries. The basic parameters of the single cell are shown in Table 5.

Table 5. Some of ternary lithium battery parameters.

Parameter	Value
Rated capacity / Ah	30
Nominal voltage / V	3.65
Voltage range / V	2.8~4.2

After determining the type and model of the battery, the numbers of parallel and serial connections also need to determine. The number of series is determined by the voltage of the motor drive control system. The number of parallels is determined by the capacity of the power battery pack. Finally, it is checked whether the power battery pack can meet the discharge current's requirement.

3.4.1. According to pure electric driving mileage. When the amphibious vehicle is silently driving, the speed is 55 km/h, and the rolling resistance coefficient f is 0.05. The power required in "2.2 in –wheel-motor's parameters design" is 26.2 kW, and the driving power of the 4 in-wheel-motor is 34.93 kW. If the silent driving distance is not less than 8 km, the required power of the in-wheel-motor during driving is:

$$W = P_{j1}t = P_{j1}\frac{s}{v_1} = 5.08 \ kWh \tag{10}$$

The power battery pack needs to provide energy:

$$\frac{W}{\eta_a\eta_b\eta_c\Delta SOC} = 11.61 \ kWh \tag{11}$$

Where η_a is the battery discharge efficiency, taking 90%; η_b is the efficiency of the in-wheel-motor, taking 90%; η_c is the ratio of the 4 in-wheel-motor's power to all the electrical equipments' power, taking 90%; ΔSOC is the depth of discharge, which is taken as 0.6.

When the safety factor is set to 1.3, a ternary lithium battery pack with a capacity W_1 of 16 kWh is selected. The capacity of the power battery pack is $\frac{W_1}{U} = 45.71$ Ah (U is the rated voltage of the in-wheel-motor controller, 350 V); since the power battery pack capacity is greater than the single battery capacity 30 Ah, the number of parallel batteries is 2.

3.4.2. According to the rated input voltage of the motor drive control system.

$$N_2 = \frac{U}{u_b} \approx 96 \tag{12}$$

Where u_b is the single cell voltage.

The power battery pack consists of two groups of 96 batteries connected in series and then connected in parallel, for a total of 192 single cells.

3.4.3. Check the discharge current of the power battery pack. The four in-wheel-motor require a power P_{j1} of 34.93 kW, which is provided by the range extender and the power battery pack. The equation is:

$$\frac{P_{j1}}{\eta_b\eta_c} = P_d = P_e\eta_1\eta_d + P_b \tag{13}$$

Where η_1 is the transmission efficiency between the engine and generator; η_d is the efficiency of the generator and controller; P_b is the power provided by the power battery pack.

When the power required by the in-wheel-motor is all provided by the power battery pack, the discharge current is the largest, and the I_{max} is calculated to be 123.2 A. The single cell's discharge current at 1 C is 30 A. When the two rows of batteries are connected in parallel, the power battery pack's discharge current at 2 C is 60 A. The maximum discharge current of the power battery pack should be 3 C and the duration is 20 min which meets the silent mileage requirement.

4. The extended-range amphibious vehicle's control strategy

Use the constant temperature control strategy. A single point control strategy is adopted to control the start and stop of the range-extender by the SOC threshold, and $SOC_{min}=50\%$, $SOC_{max}=60\%$ are selected. After the amphibious vehicle is started, it runs in the electric vehicle mode. When the battery pack's SOC drops to the minimum point, the range-extender starts, and the engine is controlled to

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operate at a stable and efficient operating point, so that the engine has a constant output power, maintaining maximum efficiency and economic.

Use the software Simulink to write the control strategies and compile them into dll interfaces. The control strategies are divided into 3 parts: the electric drive and electronic brake control strategy (Figure 3), the range-extender control strategy (Figure 4), and the PID control strategy (Figure 5). The electric drive and electric brake control strategy controls the start, stop and torque of the in-wheel-motor. The range extender control strategy controls the start and stop of the range-extender. The PID control strategy does the PID calculation by the difference between the actual speed and the set speed to control the actual speed and torque of the engine and generator to match the set value.
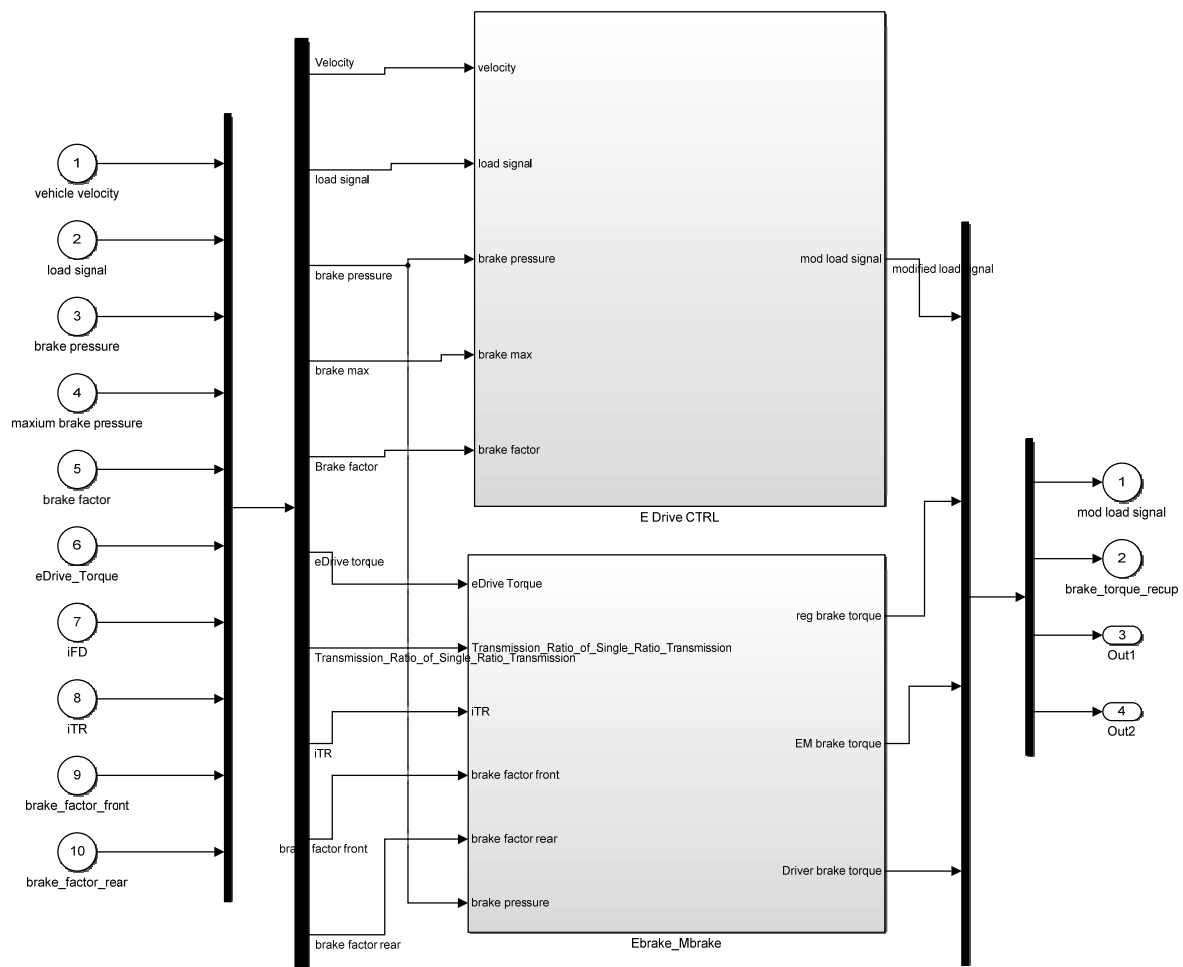
Figure 3. Electric drive and electronic brake control strategy.
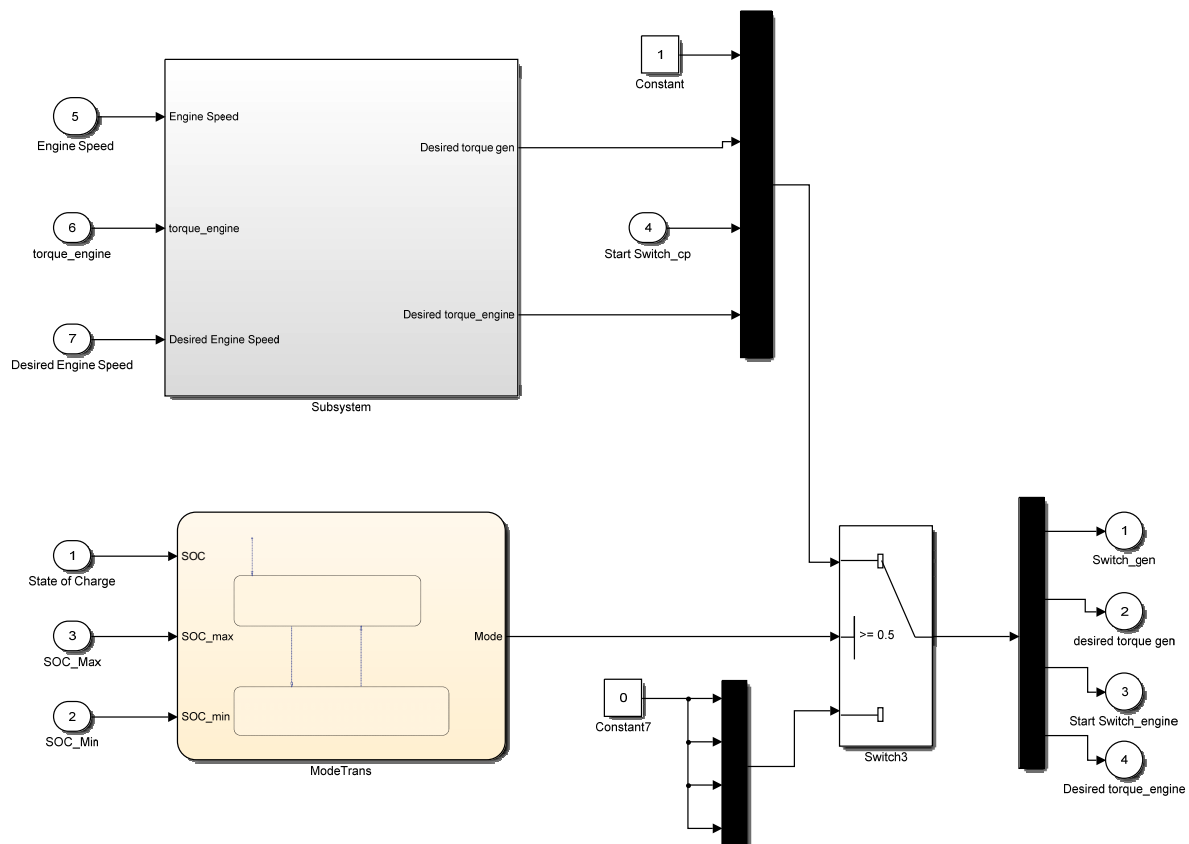
Figure 4. The range-extender control strategy.
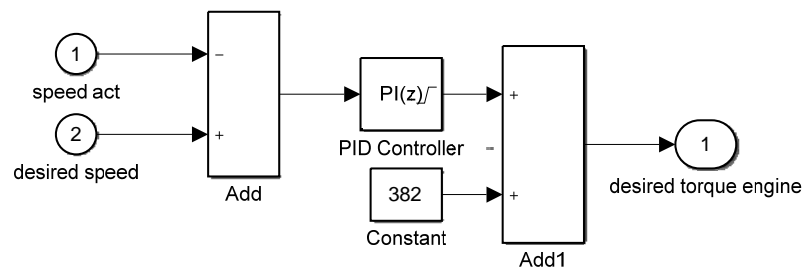
Figure 5. The PID control strategy.

5. Simulation and analysis of dynamic performance of the extended-range amphibious vehicle

After the parameters and selection of the extended-range dynammic system are determined, the vehicle simulation software Cruise is used to simulate the vehicle dynamics, and the previous dynamic system parameters' design method is verified and analyzed. Figure 6 shows the simulation model of the extended-range amphibious vehicle. Models such as the entire vehicle, driver, and power battery are provided by Cruise's standard modules. After compiling the Simulink models of the previous section about control strategy, the model can be used to control the amphibious vehicle.

As can be seen from the foregoing, the theoretical maximum speed of amphibious vehicles is 75 km/h. Therefore, there are 6 kinds of working conditions screened that meet the requirement. Two simulations with the largest acceleration are selected for simulation analysis. The two working conditions are: Japan_Mode_3_MIDTOWN and Artemis_Urban All_other_cases. The load of the amphibious vehicle is half load, 2500 kg.
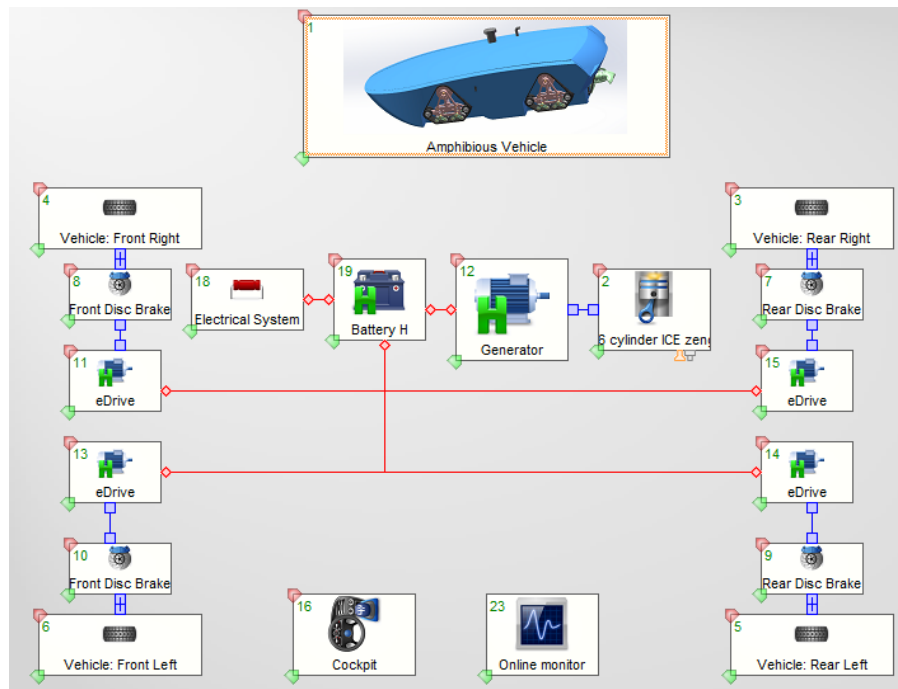
Figure 6. The extended-range amphibious vehicle's simulation model.

5.1. Dynamic performance simulation results

Figure 7 shows the simulation results for 3 Japan_Mode_3_MIDTOWN cycles.
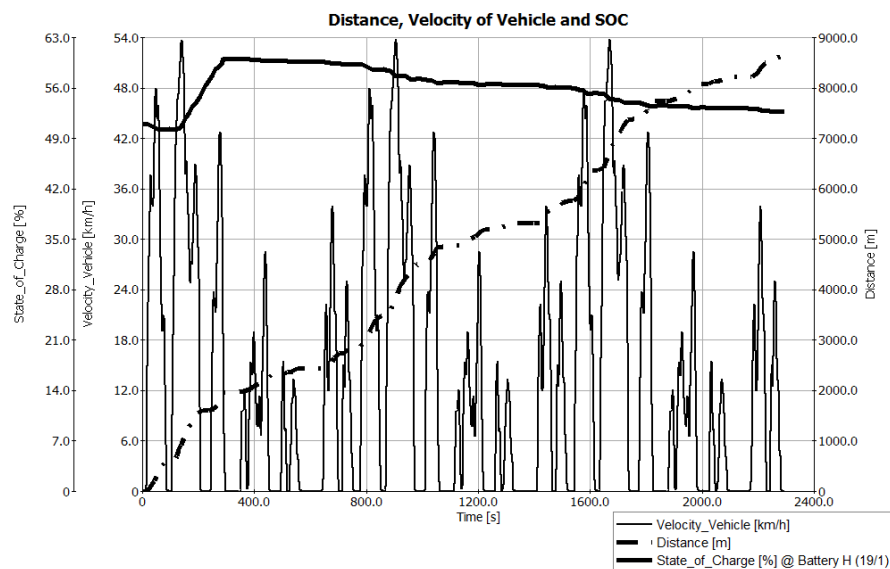
Figure 7. 3 Japan_Mode_3_MIDTOWN simulation results.

As can be seen from the speed curve, the extended-range amphibious vehicle can track the working conditions well and respond in time. In the discharge interval, the SOC value fluctuates slightly and slightly increases, because of the braking energy recovery when the vehicle decelerates.

Table 6 shows the simulation results for 3 Japan_Mode_3_MIDTOWN cycle conditions. It is difficult to match the SOC interval and the number of simulated cycles so that the SOC values of the

battery at the start and end of the simulation are exactly equal. At the end of this simulation, the SOC value of the battery is greater than the SOC value at the beginning, so the power consumption per 100 kilometers is less than zero.

**Table 6.** 3 Japan_Mode_3_MIDTOWN cycle conditions simulation results.

Parameter	Value
100 km power consumption / (kWh / 100 km)	-6.07
100 km fuel consumption / (L / 100 km)	8.00
Mileage / km	8.66

Figure 8 shows the fuel consumption and power generation during the simulation. During the start-up of the range-extender, the fuel consumption is 0.69 L; the total input energy of the generator is 10139.2 kJ; the power generation efficiency is 90.84%, and the calculated power generation is 2.56 kWh, that is, 3.11 kWh for every 1 L of diesel consumed. Converting 100 kilometers of electricity consumption into equivalent fuel consumption is 1.64 L, which is 6.36 L of total equivalent 100 km fuel consumption. It can be calculated that if the amphibious vehicle only uses diesel fuel, and the driving range on the land in Japan_Mode_3_MIDTOWN is 1257 km. The pure electric driving range of the vehicle in the discharge range of 293~2285 s is 6.68 km. In actual operation, the discharge depth of the battery is 0.6, that is, the pure electric driving range is 55.44 km, which meets the requirement of pure electric mileage.
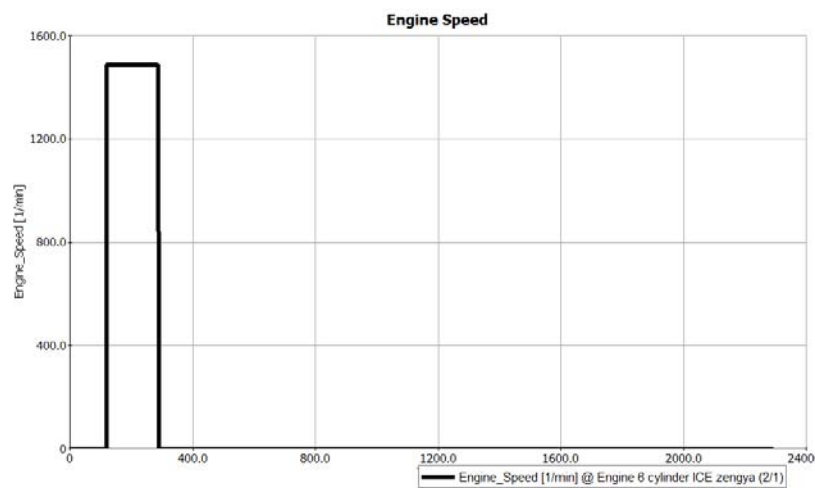
As can be seen from Figures 10~14, the engine torque is constant at 382 Nm; the rotational speed is 1502.64 r/min, and the power is 60.11 kW, which achieves the intended control objectives of Figure 2.
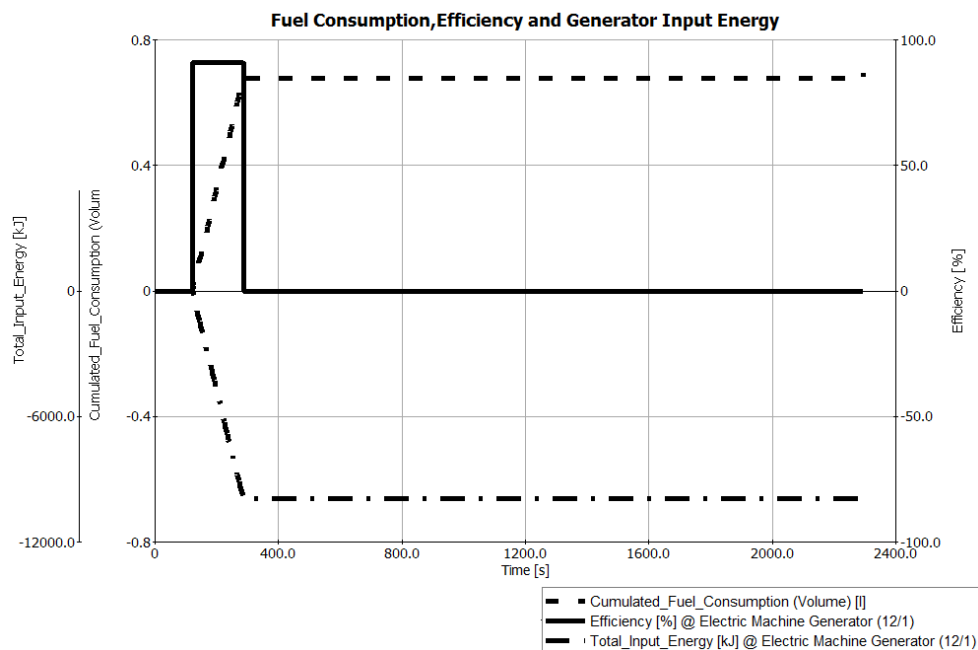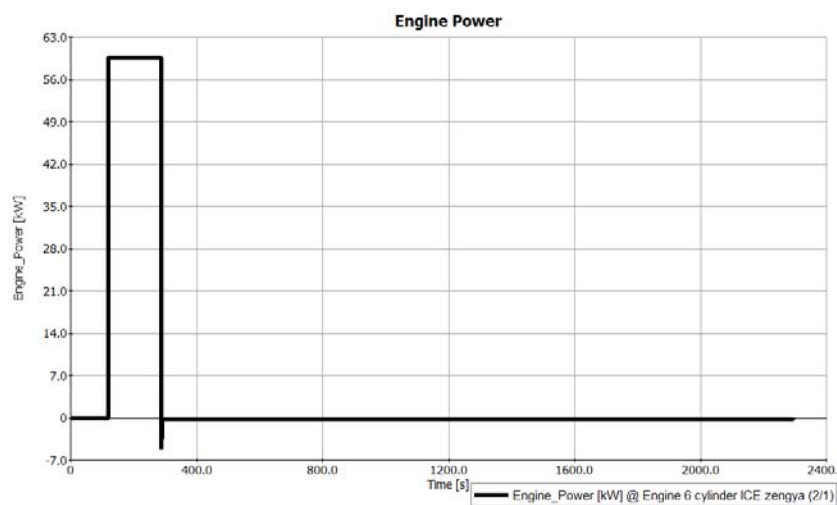

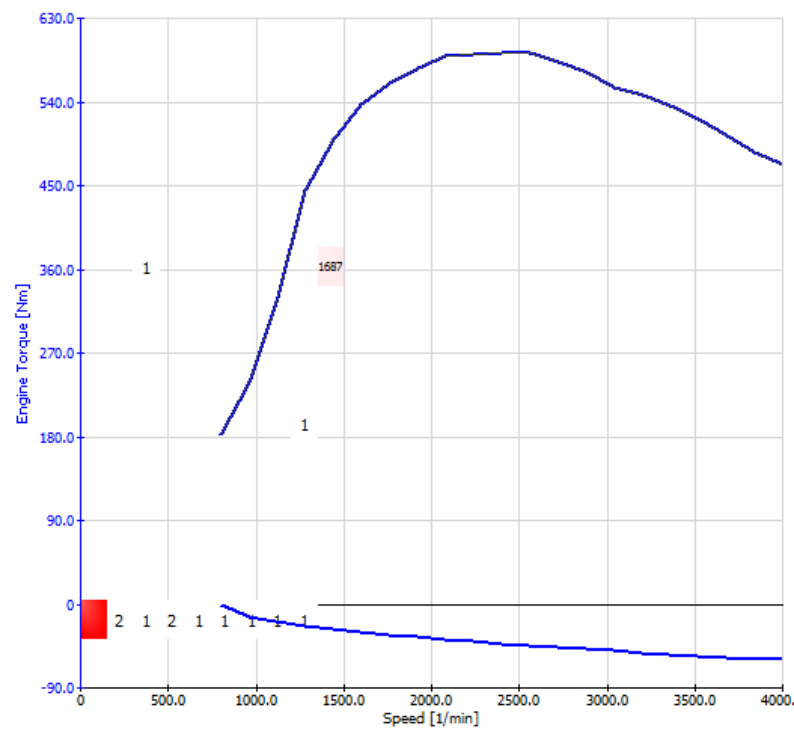**Figure 8.** Japan_Mode_3_MIDTOWN fuel consumption and power generationngine.
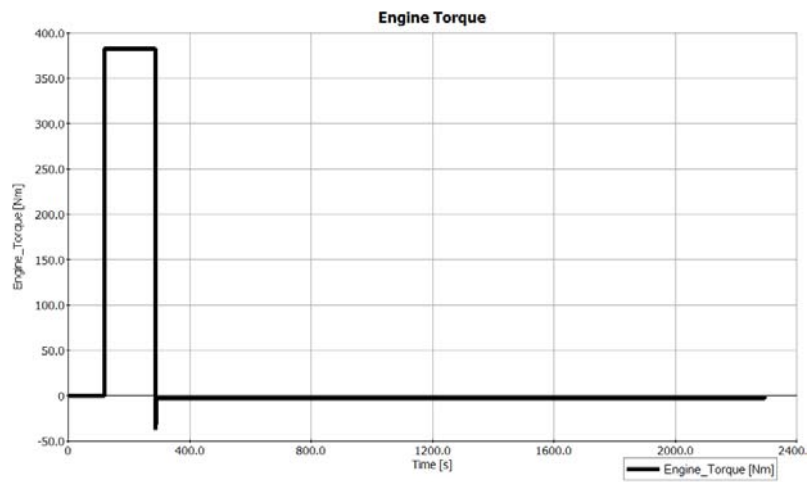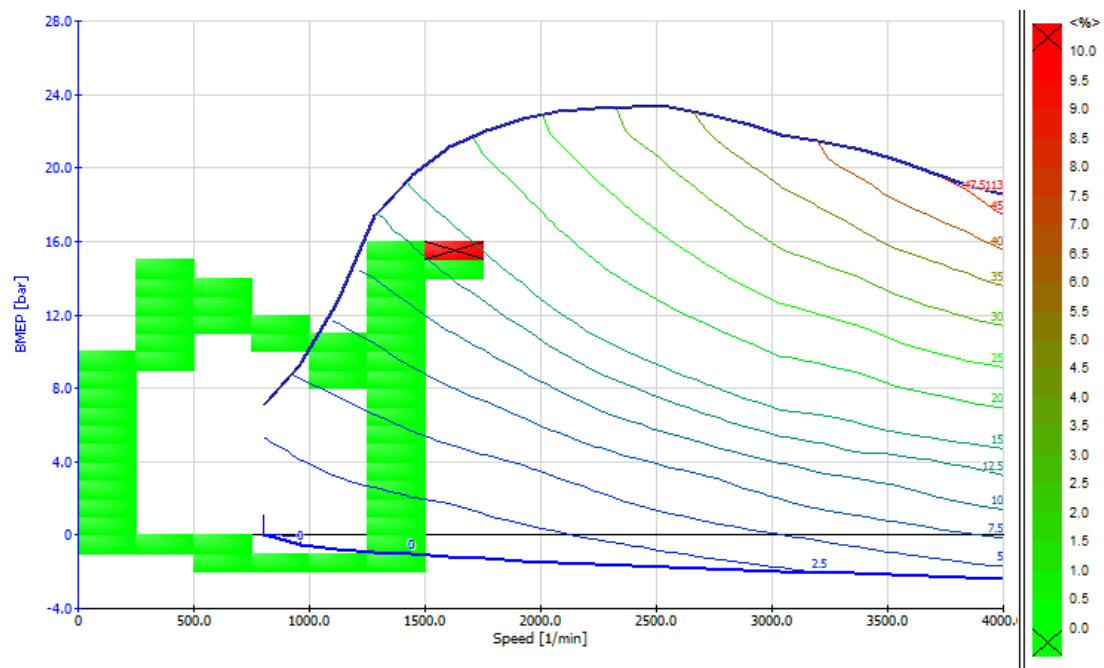
Figure 9. Engine torque.

Figure 10. Engine speed.
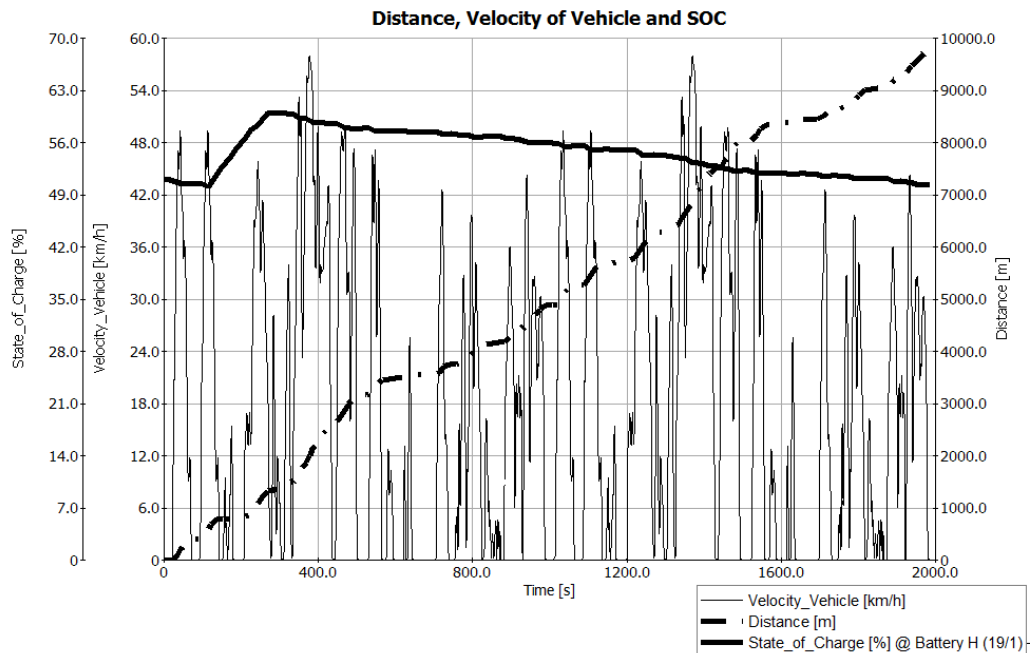

Figure 11. Engine power.

Figure 12. Engine's operating point distribution in external characteristic map.

Figure 13. Engine fuel consumption ratio.

The simulation results for the 2 Artemis_Urban All_other_cases cycles are shown in Figure 14.

**Figure 14.** 2 Artemis_Urban All_other_cases cycle simulations.

Table 7 shows the simulation results of 2 Artemis_Urban All_other_cases cycle conditions. The total equivalent fuel consumption per 100 km is 6.30 L. Under this condition, the driving range of only diesel is 1270 km. The pure electric driving range of the vehicle in the discharge interval of 271 ~ 1981 s is 8.42 km, and the pure electric driving range is 52.35 km, which meets the requirement of pure electric mileage.

Table 7. 2 Artemis_Urban All_other_cases cycle simulation results.

| Parameter	Value
100 km power consumption / (kWh / 100 km)	-1.03
100 km fuel consumption / (L / 100 km)	6.58
Mileage / km	9.76

5.2. Maximum grade simulation result
Set the Climb Performance calculation task. The simulation results are shown in Figure 15. In the low speed section 0～20.96 km/h, the climbing degree is above 122%, that is, the slope angle is above 50°, which meets the requirement of climbing 18°.
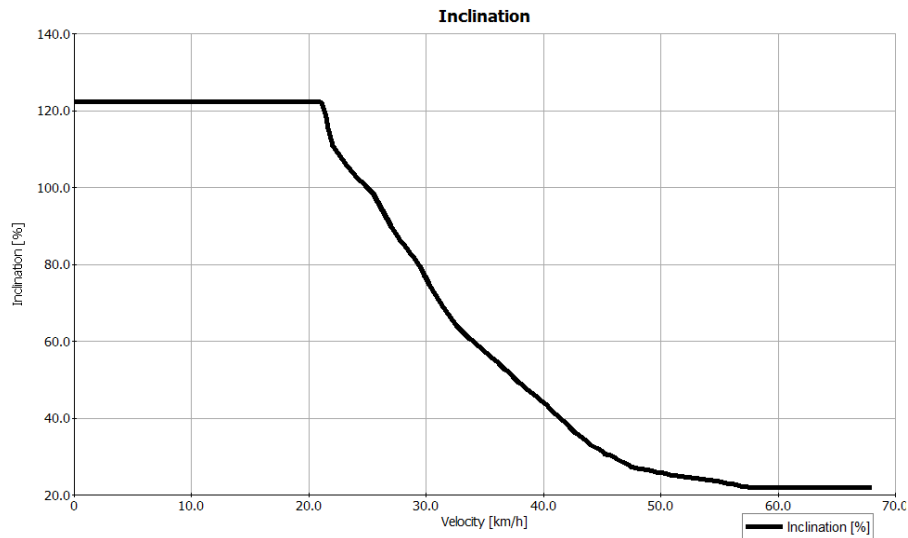
Figure 15. Climbing curve.

5.3. Acceleration capability simulation result

Set the acceleration task from 0 to 70 km/h. The simulation results are shown in Figure 16. The acceleration in the initial stage of 0~0.5 s can reach 8.9 m/s^2; the acceleration time of 70 km/h is 5.2 s; the acceleration distance is 65 m; the acceleration time of 55 km/h is 3.1 s; the acceleration distance is 31 m. During the low speed section, the acceleration performance is especially good.
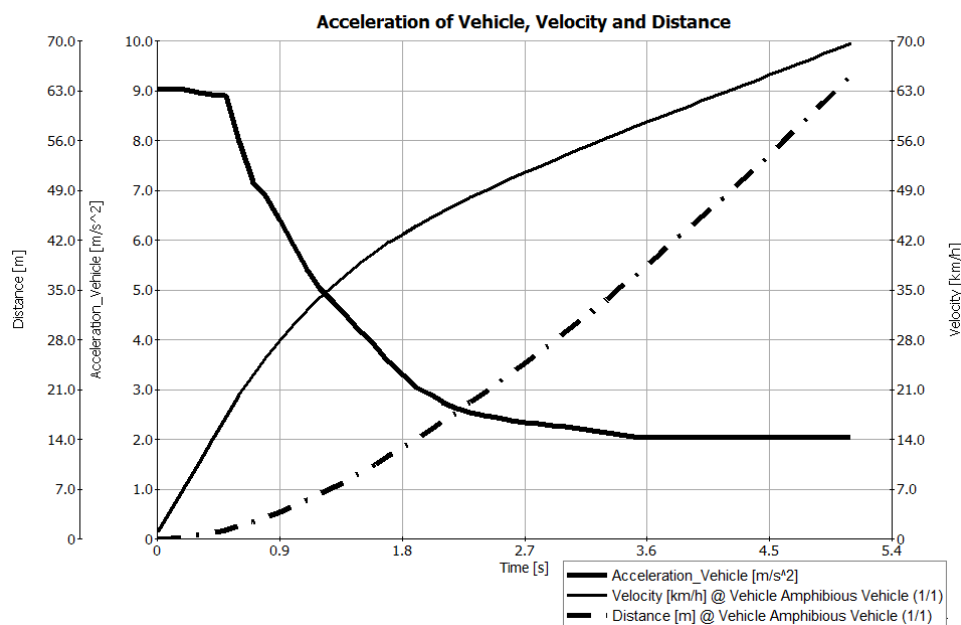
Figure 16. Full load acceleration curve.

6. Conclusion

This paper mainly analyzes the parameters' design, components' selection, and control strategy design and simulation task analysis of the extended-range amphibious vehicle dynamic system. Starting from the vehicle parameters and design indicators, the design calculation of the in-wheel-motor, the range-

extender and the power battery pack is emphasized. A design method of the dynamic system is given, and a control strategy for effectively controlling the amphibious vehicle is proposed. The following conclusions are drawn:

1) The extended-range amphibious can track the conditions of Japan_Mode_3_MIDTOWN and Artemis_Urban All_other_cases well, and can follow the external conditions and respond in time;

2) Pure electric driving mileage, maximum road mileage and water mileage are all satisfied;

3) Adopting the constant temperature control strategy, the engine works at a good economical operating point when the range-extender is started. The constant speed is 1500r/min, and the torque is constant at 382 Nm;

4) 0-55km/h acceleration time is 3.1s, and 0-70km/h acceleration time is 5.2s. The acceleration performance is excellent;

5) The climbing degree is above 50° when the speed of the vehicle is 0~20.96 km/h, and the climbing performance is excellent.

In summary, the parameters of the extended-range amphibious vehicle's dynamic system are reasonable. The components are selected and matched well, and the control strategy designed meets the requirements. The design of the amphibious vehicle conforms to the using requirements and performance indicators.

Acknowledgments

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