Optimal Control Technology of Electric Power Load Distribution of Submarine Cable Salvage Robot

Duan Yubing¹, Hu Xiaoli¹, Gu Chao¹, Sun Xiaobin², Yao Jinxia¹, Yang Bo² and Zhang Hao¹*

¹ State Grid Shandong Electric Power Research Institute, Jinan, China
² State Grid Shandong Electric Power Company, Jinan, China
*Email: sdqzzh@163.com

Abstract. The submarine cable salvage robot needs energy storage device as power supply or backup power supply when working underwater. The optimal control strategy of load distribution can realize the reasonable distribution of electric load among multiple energy storage devices according to the different residual capacity of energy storage devices, thus improving the energy utilization efficiency of energy storage devices and prolonging the operation time of salvage robots.

1. Preface
With the development and improvement of underwater vehicle technology[1-2], power companies have applied it to submarine cable salvage operations, thereby improving the efficiency of submarine cable salvage work and reducing risks. The submarine cable salvage robot should be equipped with underwater propeller, caterpillar chassis, high-pressure water gun, manipulator, camera, lighting and other equipment. The use of these equipment requires a large amount of electricity.

According to the control mode, the submarine cable salvage robot can be divided into two types: non-cable type and cable type. The cable-free submarine cable salvage robot relies entirely on its own energy storage device to provide power, and the cable-type can obtain power supply through umbilical cord cable when it works normally. However, in order to deal with unexpected accidents, the cable-type submarine cable salvage robot will also equip the energy storage device as a backup power supply.

Considering the limitations of volume, weight, cost and other factors, the capacity of energy storage devices that can be carried by submarine cable salvage robots is limited. How to effectively and fully utilize these energy has become a research hotspot in this field.

Most of the existing energy storage devices are composed of multiple energy storage units in series and parallel. Current sharing control for parallel energy storage units is the most commonly used energy management method at present[3-8]. Due to the difference of discharge characteristics, the residual capacity of each energy storage unit will be different. Therefore, under the current sharing control mode, the energy storage unit with less residual capacity will discharge first, which makes other series-parallel energy storage units unable to work properly, that is, the remaining energy can not be released, thus reducing the energy utilization efficiency of the whole energy storage device.

In view of the demand of submarine cable salvage robot for energy management and the shortcomings of current sharing control, how to improve the energy utilization efficiency of energy
storage devices through energy management has become the focus of this paper.

2. Control Circuit and Control Strategy Design

At present, detection technology of residual capacity of energy storage devices has been mature. How to use the detected residual capacity, through the independent regulation of each energy storage unit, ultimately realize the load distribution according to the amount of residual capacity of each energy storage unit is the main problem to be solved in this paper.

Based on the above objectives, the specific design scheme of load distribution control strategy for residual capacity matching is as follows:

● During operation, the energy storage unit detects its output current $I_{out}$ and residual capacity SOC, calculates their quotient, and defines them as the load factor $k_L$ of the energy storage unit.

$$k_L = \frac{I_{out}}{SOC}$$

● The calculated load coefficient $k_L$ is converted into analog signal and used as input of bus signal generation circuit. The bus signal generation circuit is shown in figure 1. The input signal $k_L$ is amplified by an operational amplifier circuit and sent to the common bus by a diode. All bus signal generating circuits of parallel operation energy storage units share the same common bus, that is, all parallel operation energy storage units send their own load coefficient signals to the same common bus. According to the characteristics of diode unidirectional transmission, the signal on the final common bus is the maximum of all load coefficient signals, that is, the maximum load coefficient $k_{L_{max}}$.

\[\text{Figure 1. Bus signal generating circuit}\]

● The energy storage unit uses the difference value $\Delta k$ between the maximum load coefficient $k_{L_{max}}$ and its own load coefficient $k_L$ as the input of the load distribution controller. The output of the load distribution controller works together with the output of the given voltage value, the output voltage feedback value and the output current feedback value. After the processing of the voltage controller and the current controller, the output current of the energy storage unit is adjusted. The specific control block diagram of the load distribution control strategy with matched residual capacity is shown in figure 2. The control model consists of voltage sampling (VS), current sampling (CS), voltage controller (VC), current controller (CC), PWM modulator, buck circuit, load distribution controller (LDC) and load coefficient calculation circuit (LCCC).
When each energy storage unit completes the load distribution adjustment, the energy storage device enters the steady-state operation stage. In steady-state operation, the load coefficients of each energy storage unit are approximately equal to the maximum load coefficient $k_{L_{\text{max}}}$, which achieves the control purpose of load distribution according to the amount of residual capacity, and the ratio of load current of each energy storage unit is equal to the ratio of its residual capacity.

### 3. Simulation verification and analysis

Aiming at the above-mentioned load distribution control strategy of residual capacity matching, a simulation model is built in Matlab software. The specific simulation work includes:

- Kalman filter algorithm is used to detect the residual capacity of energy storage device.
- Because the load distribution controller takes the maximum load coefficient as the control target, the proportional controller is adopted to design the controller.
- Both voltage controller and current controller adopt PI controller.
- According to the parameters of the existing experimental platform, the simulation circuit is built, in which the charge-discharge circuit is bidirectional Buck circuit.
- The energy storage device is composed of three energy storage units in parallel.
- The ratio of residual capacity of three energy storage units is 5:3:2.

The simulation results of load distribution using current sharing control are shown in figure 3. In order to observe the control effect conveniently, the residual capacity of the three energy storage units is small in the simulation. From the output current simulation waveform, it can be seen that the output current of the three energy storage units is basically the same in the initial stage of operation, and their discharge rate is the same. At about 2.2s, the energy storage unit 3 has to withdraw from operation due to the decrease of the remaining capacity to zero, and then the energy storage unit 2 and 3 operate in parallel, and at about 2.9s, the energy storage unit 2 also withdraws from operation due to the decrease of the remaining capacity to zero. Subsequently, the energy storage unit 3 operates alone until the discharge is completed.

However, the output current of energy storage unit 3 has exceeded its own safety limit when it runs alone, so, from the point of view of safe operation, the whole energy storage device can only run to 2.9s at most, that is, after discharge of energy storage unit 2, it has to withdraw from operation. As a result, not less than 6% of the remaining energy can not be utilized. In practice, if other constraints are considered, the running time may be shorter. It can be seen from the current waveform that in the period of 0.5-2.2s, the control effect of the output current of the energy storage unit 3 has begun to deteriorate, and the ripple of the output current of other energy storage units has begun to increase. Similarly, in the period of 2.2-2.9 seconds, the effect of current sharing has also been significantly affected.

**Figure 2.** Load distribution control strategy block diagram for residual capacity matching
Under the same model and parameters, the simulation results of load distribution control strategy using residual capacity matching are shown in Figure 4. From the simulation results, it can be seen that the output currents of the three energy storage units are not the same, but 5A, 3A and 2A respectively, because the distribution of load current is proportional to the amount of residual capacity. Although the discharge rate of each energy storage unit is not the same, the discharge termination time is basically 3.7s, that is, the whole energy storage device can operate safely and steadily in the period of 0-3.7s, and the current changes smoothly with less ripple content.

After 3.7 seconds, due to the control error, the energy storage unit 3 is still the first to discharge, which also affects the output of the other two energy storage units. However, for the residual capacity matching load distribution control, the final out-of-control time caused by control errors is very short, and the overall energy storage device can be directly withdrawn from operation at 3.7s. Even so, compared with the current sharing control, the safe operation time of the energy storage device is increased by about 27.6%, and the energy utilization rate is approximately 100%.

Figure 4 (c) is the output current simulation waveform of three energy storage units under sudden load change. After the sudden load change occurs, under the control of control algorithm, each energy storage unit can not only quickly adjust the output current, but also basically follow the principle of capacity matching in the dynamic process of load current distribution. Therefore, the control strategy not only has good steady-state performance, but also has excellent dynamic characteristics.
4. Experimental verification and analysis

On the basis of simulation and verification, the experiment platform is used to verify the control strategy of residual capacity matching load distribution in parallel operation of three energy storage units. The experimental waveform is shown in figure 5.

From the current and voltage waveforms of steady-state operation, it can be seen that the load current distribution of three energy storage units in steady-state operation conforms to the principle of residual capacity matching, and the bus voltage is stable. But the output current of two energy storage units appears obvious overshoot and short-term repetitive regulation during power-on startup. This is mainly because the PI controller with fixed PI parameters is adopted in the design and implementation of the control strategy, and the working states of the three energy storage units are different, so the dynamic changes of the three energy storage units can not be completely consistent.

The dynamic performance of the control strategy is basically consistent with the simulation results when the load changes abruptly. The output voltage has a peak of less than 5%, which can fully meet the power demand of normal load. But it is also because of the parameter design of PI controller, which affects the current change in the process of dynamic regulation.

During the experiment, because of the limited duration of the experiment, it is impossible to plot the curve of residual capacity change in the corresponding time. However, the experimental data and waveforms are consistent with the simulation results, which verifies the feasibility and effectiveness of the residual capacity matching load distribution control strategy.

5. Conclusion

Compared with the existing energy management technologies of energy storage devices such as current sharing control, the load distribution control strategy with matched residual capacity has the following characteristics:

- The control strategy is based on the load coefficient as the control objective, so that each energy storage device can reasonably distribute the load according to the size of the remaining capacity.
Under the control of this control strategy, each energy storage unit will adjust its own discharge rate, so that the discharge time of multiple parallel operation energy storage units with different residual capacity is consistent. It can not only prolong the power supply time of the whole energy storage device, but also make full use of the stored energy.

Under the control of the control strategy, the energy storage device not only has excellent steady-state operation performance, but also has good dynamic regulation characteristics, so there is no need to adjust or switch the control strategy according to the change of operation status.

If the remaining capacity is replaced by rated capacity, the parallel operation control of energy storage devices with different rated capacity can also be realized by using this control strategy.

In conclusion, the load distribution control strategy with matching residual capacity can meet the power management requirements of submarine cable salvage robot for energy storage devices and improve its performance.

Acknowledgment
This work was supported by Research on Operation Technology of Cross-sea High Voltage DC Submarine Cable and Key Technologies of Detection Robot, which was funded by the Technology Projects of State Grid Corporation of China. This support is very gratefully acknowledged.

Reference
[1] Zhao Junhai, Zhang Meirong, Wang, Shuai. Application and development trend of tether management system (TMS) for ROV. Ship Building of China, v 55, n 3, p 222-232, September 1, 2014
[2] Tehrani Nima Harsamizadeh, Heidari Mahdi, Zakeri Yadollah, Ghaisari Jafar. Development, depth control and stability analysis of an underwater Remotely Operated Vehicle (ROV). 2010 8th IEEE International Conference on Control and Automation, ICCA 2010, p 814-819, 2010
[3] Renaudineau H, Houari A, Shahin A, et al. Efficiency Optimization Through Current-Sharing for Paralleled DC–DC Boost Converters With Parameter Estimation. IEEE Transactions on Power Electronics, 2013, 29(2):759-767.
[4] Bartal P, Hamar J, Nagy I. Efficiency improvement in modular DC/DC converters using unequal current sharing. Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2012 International Symposium on. IEEE, 2012:275-280.
[5] Bartal P, Hamar J, Nagy I. Parallel DC/DC Converters with Multi-Agent Based Multi-Objective Optimization for Consumer Electronics. 2011 IEEE International Conference on Consumer Electronics -Berlin (ICCE-Berlin), 2011:276-280.
[6] Bartal P, Nagy I. Game Theoretic Approach for Achieving Optimum Overall Efficiency in DC/DC Converters. Industrial Electronics IEEE Transactions on, 2014, 61(7):3202-3209.
[7] Suyong Chae. Digital current sharing method of parallel interleaved DC-DC converters using input ripple voltage. IEEE TRANSACTIONS ON POWER ELECTRONICS, vol. 27, No. 7, July 2012:3277-3291
[8] Renaudineau H, Houari A, Shahin A, et al. Efficiency Optimization Through Current-Sharing for Paralleled DC–DC Boost Converters With Parameter Estimation. IEEE Transactions on Power Electronics, 2013, 29(2):759-767