Research on Energy Optimizing Management Technology of Submarine Cable Salvage Robot

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Abstract. In the design of submarine cable salvage robot, considering the limitations of weight, space, cost and many other factors, the robot can only carry energy storage devices with limited capacity. In the process of dynamic regulation, current sharing technology is used to ensure safe operation. In the steady state operation, through the optimization of load distribution scheme, the optimal control of overall efficiency of energy storage device can be achieved, the utilization efficiency of storage energy can be improved, and the overall operation performance of electrical system can be improved.

1. Preface

With the development of submarine cable salvage robot technology\cite{1,2}, the efficiency of submarine cable salvage work has been effectively improved and the danger of salvage personnel has been reduced. Salvage robots are equipped with many electrical equipment, such as propellers, robotic arms, video lighting systems, etc., which need to consume a lot of electricity.

There are two kinds of submarine cable salvage robots. One is cable type, which requires the mother ship to provide electricity through umbilical cord cable; the other is cable-free type, which carries its own energy storage device. However, considering some emergencies, cable-based robots will also install energy storage devices as emergency power supply.

In the design process of submarine cable salvage robot, considering the limitation of many requirements such as lightness, flexibility, easy control and so on, the capacity of energy storage device that the robot can carry is very limited, so it is necessary to design an optimization scheme to solve the problem of how to effectively and fully utilize these energy.

At present, the commonly used energy storage devices are composed of multiple energy storage units in series and parallel, and current sharing control is the most commonly used energy management strategy for parallel operation of energy storage units\cite{3-6}. However, the difference of efficiency characteristics of energy storage units (e.g. different manufacturers, different types of energy storage units, even if the design parameters and specific structures are exactly the same, due to the aging of internal devices, parasitic parameters and other factors, there must be some differences in efficiency characteristics) makes the current sharing control can not make the steady-state operation efficiency of energy storage devices optimal. For high-power energy storage devices, small efficiency differences mean a lot of waste of energy.

Therefore, when designing the control strategy of energy storage device for submarine cable salvage robot, optimizing the utilization efficiency of storage energy and overcoming the shortcomings of current sharing control have become the core of this paper.
2. Analysis of efficiency characteristics

Each energy storage unit contains charging and discharging circuits and energy storage devices. Since it is impossible to analyze the efficiency of energy storage devices according to the definition of efficiency, and considering that the energy storage device is in discharge state when the submarine cable salvage robot works, the efficiency characteristics of energy storage devices studied in this paper are based on the efficiency characteristics of the discharge circuit.

Discharge circuit losses of energy storage devices mainly include inductance loss, capacitance loss, power switching device conduction loss and so on. If the influence of bad environment temperature on circuit parameters and the non-linear characteristics of parasitic parameters are neglected, the power loss of energy storage devices can only be considered to be related to the output current, that is to say, the efficiency characteristics of energy storage devices can be regarded as a function of efficiency on the output current.

If the energy storage device is composed of $n$ energy storage units in parallel, the overall efficiency of the energy storage device can be expressed by formula (1):

$$
\eta = \frac{P_{\text{out1}} + P_{\text{out2}} + \cdots + P_{\text{outn}}}{P_{\text{in1}} + P_{\text{in2}} + \cdots + P_{\text{inn}}} = \frac{\sum_{i=1}^{n} P_{\text{outi}}}{\sum_{i=1}^{n} P_{\text{ini}}} \eta_1 + \sum_{i=1}^{n} P_{\text{outi}} / \eta_{ni}
$$

(1)

Where $P_{\text{outi}} (i=1,2,...,n)$ is the output power of the discharge circuit of the $i$th energy storage unit; $P_{\text{ini}} (i=1,2,...,n)$ is the input power of the discharge circuit of the $i$th energy storage unit; $\eta_i (i=1,2,...,n)$ is the efficiency of the energy storage unit $i$th.

Since the efficiency of the energy storage device is a function of the output current, the $\eta_1, \eta_2, ..., \eta_n$ in formula (1) can be expressed by the output current of each energy storage unit, so the overall efficiency of the energy storage device can also be expressed by the function of the output current of each energy storage unit. That is to say, formula (1) can be simplified as formula (2).

$$
\eta = f(I_{o1}, I_{o2}, ..., I_{on})
$$

(2)

$I_{o1}(i=1,2,...,n)$ is the output current value of the $i$th energy storage unit.

Because the efficiency of energy storage devices is related to $I_{o1}$, $I_{o2}$, ..., $I_{on}$ and is a multivariable high-order function of current, so the load distribution based on efficiency optimization can be transformed into the problem of solving the maximum efficiency of the system, that is:

$$
\max \eta = \max f(I_{o1}, I_{o2}, ..., I_{on})
$$

(3)

$$
\sum_{i=1}^{n} I_{o1} = \frac{I_{\text{load}}}{\eta(1) I_{o1}}
$$

Considering that the output current of each energy storage unit has a certain range, for example, the lower limit of the output current of the energy storage unit can be set as it's critical continuous current value, while the upper limit of the current is it's rated current value, and the upper and lower limits of each energy storage unit may be different, but the sum of the output current of all energy storage units must be equal to the total load current. Then the load distribution problem of energy storage devices based on the optimal efficiency is transformed into the maximum efficiency problem with constraints, and the constraints are brought into the formula (3) to obtain:

$$
\max f(I_{o1}, I_{o2}, ..., I_{on}) = \max \frac{I_{\text{load}}}{\sum_{i=1}^{n} \eta(I_{oi})}
$$

(4)

$$
I_{\text{min}}, I_{\text{max}} (i = 1, 2, ..., n)
$$

$I_{\text{min}} (i = 1, 2, ..., n)$ is the minimum current value of the $i$th parallel energy storage unit.
\[ I_{\text{max}} (i=1,2,\ldots,n) \] —— Rated output current value of the \( i \)th parallel energy storage unit;

\[ I_{\text{load}} \] —— Total load current value of energy storage device.

By introducing the equation in formula (4) into the efficiency formula, can get the result:

\[
\text{max } f(I_{o1}, I_{o2}, \ldots, I_{o(n-1)}) = \max \left( \sum_{i=1}^{n-1} \eta_i(I_{oi}) + \frac{I_{\text{load}} - \sum_{i=1}^{n-1} I_{oi}}{\eta_i(I_{\text{load}} - \sum_{i=1}^{n-1} I_{oi})} \right) \tag{5}
\]

\[
I_{\text{min}} \leq I_{oi} \leq I_{\text{max}} (i = 1, 2 \ldots n-1)
\]

\[
I_{\text{min}} \leq I_{\text{load}} - \sum_{i=1}^{n} I_{oi} \leq I_{\text{max}}
\]

Therefore, the load allocation problem based on the optimal efficiency can be simplified to the problem of finding the maximum value of the \( n-1 \) element function with constraints. In order to obtain the function extreme value, the commonly used algorithms are mountain climbing, particle swarm optimization, neural network, genetic algorithm, etc. Because particle swarm optimization algorithm has the advantages of simple design, high precision and fast convergence, this paper takes it as the calculation method for efficiency optimization, and finally works out the load distribution scheme for the optimal efficiency of energy storage device.

3. Particle swarm optimization design

In the process of optimization, the particle swarm optimization algorithm first initializes a set of random solutions, namely a random particle swarm, and then searches for the optimal solution of the objective function by using the iterative method. In each iterative search, the particle will adjust its position and search speed through the optimal solution found by itself and the optimal solution of the whole population. The flow chart is shown in Figure 1.

The objective function of particle swarm optimization is the total efficiency of the energy storage device, and the particle is the current value of each energy storage unit. In order to ensure the continuity of the inductive current, the output current of the energy storage unit should be greater than 0, and the sum of the current is the total load current, so the position range of the particles should be set according to the actual operation demand. Generally, particle swarm optimization algorithm is used to select 20-40 particles in the system. Considering the complexity of the objective function of efficiency optimization, the particle number is 50 and the maximum iteration number is 100.

Inertia weight \( w \) is a measure of the proportion of global optimization and local optimization in the system. In the initial stage of iterative search, a large inertia weight can avoid falling into the local optimal solution. In the later stage of search, a small inertia weight can help speed up the convergence of particles. Based on the above theory, the initial value of inertia weight is set as 0.9, and the value gradually decreases by 0.1 in the search process. Such linear decline method can obtain the more accurate optimal solution.

Learning factors \( c_1 \) and \( c_2 \) are used to balance the self-cognition ability and social cognition ability of particles, and are used to control the steps of particles moving towards individual optimal and global optimal respectively. Generally, they are set as positive numbers. After design verification, when \( c_1=1.3 \) and \( c_2=1.7 \), the system can effectively find the optimal efficiency point and search faster.

In this paper, the annular neighborhood method is used as the search strategy of efficiency optimization particle swarm optimization. In order to eliminate falling into local optimum, local adaptive operator is added to the algorithm to optimize. The formula is as shown in formula (6). The objective function value of this position is randomly selected and compared with the historical maximum value of particle swarm. If the random position value is larger than the historical maximum
value of particle swarm, the historical maximum value is replaced. On the contrary, the previous maximum is retained, which can effectively avoid the algorithm falling into the local maximum.

$$X_i = X_{\text{min}} + (X_{\text{max}} - X_{\text{min}}) \times \text{rand}$$  \hspace{1cm} (6)

$X_i$--Random location of particle swarm;
$X_{\text{min}}$--Minimum particle swarm position;
$X_{\text{max}}$--Maximum position of particle swarm;
rand--Random number, value is (0,1) interval.

![Particle swarm optimization search flow chart](image)

**Figure 1.** Particle swarm optimization search flow chart

4. **Control strategy design**

In the process of dynamic regulation of energy storage devices such as start-up or load sudden change, because the energy storage state of inductance, capacitance and other components in the circuit changes, the efficiency value at this time does not have theoretical analysis and practical reference value, so it is meaningless to adopt efficiency optimization control (EOC) in the dynamic process, and may even affect the safety of energy storage devices. In the dynamic process, the selection of control strategy should be to ensure the safe operation of each energy storage unit as the core. Therefore, this paper designs a composite control strategy which combines dynamic current sharing control with steady-state efficiency optimization control.
Taking the parallel operation of two energy storage units as an example, the control block diagram of the composite control strategy is shown in Figure 2. It consists of efficiency optimization controller (EOC), load distribution controller (LDC), current sharing controller (CSC), state determination controller (SDC), voltage controller (VC), current controller (CC) and PWM modulator. All the controllers share the same efficiency optimization controller. The current sharing controller is designed by maximum current method, and the load distribution controller is designed by proportional controller. $I_{o1}$ and $I_{o2}$ are output currents of two energy storage units, $I_{load}$ is load current, $I_{ref1}$ and $I_{ref2}$ are given for efficiency optimization load distribution based on particle swarm optimization. If the amplitude of $I_{load}$ does not change obviously in several continuous judgment periods, it can be considered that the circuit is in steady state operation, and the selection switch $S$ is connected to the output terminal of the load distribution controller to realize the optimal control of the efficiency of the energy storage device; on the contrary, the selection switch $S$ is connected to the output terminal of the current sharing controller to realize the current sharing control between the energy storage units.

5. Simulation and experiment

In this paper, two-way Buck circuit is used as charging and discharging circuit, in which inductance $L=15\text{mH}$ and capacitance $C=250\mu\text{F}$. The efficiency optimization of energy storage devices running in parallel with two energy storage units is simulated and experimentally verified.

Figure 3 (a) is the simulation results of the output voltage of the energy storage device and the output current of the two energy storage units when the total load current is $10\text{A}$. From the simulation waveform of current, it can be seen that the current sharing control is adopted in the start-up stage of power supply. The output currents of the two energy storage units are basically the same. After a period of steady-state operation, the control system begins to carry out efficiency optimization calculation. When the maximum efficiency is calculated, the output current of one energy storage unit is $3.93\text{A}$, and the other is $6.07\text{A}$. The calculation results are regarded as the given value of output current. Finally, the output current of the energy storage unit is stable around $3.93\text{A}$, and the output current of the energy storage unit is stable around $6.07\text{A}$. Compared with the current sharing control, the efficiency of the energy storage device is improved by about $1\%$. During the switching process of the control strategy, the output voltage remains stable. By changing the load size and calculating the corresponding efficiency value, the efficiency characteristic curves of current sharing control and efficiency optimal control are obtained as shown in Figure 3 (b). It can be seen that within the normal working range, the efficiency optimal control can obviously improve the working efficiency of energy storage devices.

And simulation for the experimental results are shown in Figure 4, although due to the actual device parameters and simulation parameters vary, leading to the optimal load distribution of power.
point and efficiency characteristics of the measured curve must be different from the simulation results, but the experimental results also verify the effectiveness of efficiency optimization control strategy, and the feasibility of the hybrid control strategy.

![Simulated waveform](image)

**Figure 3.** Simulated waveform

![Experimental waveform](image)

**Figure 4.** Experimental waveform

6. Conclusion

The simulation and experiment show that the efficiency optimization control algorithm and the composite control strategy have the following characteristics:

- Particle swarm optimization (PSO) has the advantages of simple design, fast convergence speed, on-line optimization and practicability of efficiency optimal control strategy.
- Under steady-state operation, the optimal efficiency control achieves the efficiency optimization of energy storage system and improves the utilization efficiency of storage energy.
- The design of control method switching criterion in compound control strategy can realize flexible and safe switching of two control methods.
- In the dynamic process, the safety and reliability of energy storage system can be effectively improved by switching the control strategy to current sharing control.

To sum up, the composite control strategy can not only ensure the safe and reliable operation of the submarine cable salvage robot's electrical system, but also effectively improve the energy utilization efficiency of the energy storage device and improve the performance of it's electrical system.

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