A Multi-Agent Based Method for Service Restoration in Shipboard Power System

Abstract. The shipboard power system (SPS) supplies energy to electric loads on ships. If the power supply of SPS is interrupted by a fault, it is important to restore the power system as soon as possible. Many approaches have been taken on the service restoration of SPS, but most of them use a centralized method and cannot meet the Navy's needs for fight-through survivability and high reliability. This paper improves the mathematical programming method proposed in the early literature and presents a multi-agent system framework performing system restoration for Navy ship. In the MAS, all agents have the ability to collect information, process data and make reasonable decisions independently according to different environment. The MAS is implemented based on Java Agent development framework (JADE). The simulation results of typical SPS service restoration cases demonstrated the feasibility and the advantages of the proposed MAS.

Streszczenie. Gdy system zasilania okrętowego zostanie przerwany bardzo ważne jest aby powrócić do stanu sprzed uszkodzenia jak najszybciej. W artykule zaproponowano ulepszoną metodę wykorzystującą system typu multi agent. Każdy z agentów ma możliwość zbierania informacji, przetwarzania danych i podejmowania decyzji w różnych okolicznościach. (Metoda przywracania sprawności okrętowego systemu zasilania wykorzystująca system typu multi agent)

Keywords: Shipboard power system, service restoration, integer programming, multi-agent system.

Słowa kluczowe: system zasilania okrętowego, przywracanie sprawności, metoda multi-agent.

1. Introduction

The shipboard power system (SPS) provides energy to electrical loads on ships for battle, communication, navigation, operation and so on. The reliability and stability of power supply are important for SPS, especially under battle conditions. During the SPS operation, some part of the system may be unavailable because of faults or battle damage. In this situation, it is imperative to isolate the fault immediately and restore the power supply quickly to increase the survivability and reliability of SPS.

The method proposed to solve service restoration problems can be roughly classified into two types: centralized methods and distributed methods. The centralized methods include heuristics [1-3], expert systems (ESs) [4, 5], and mathematical programming (MP) [6, 7], while the distributed methods are mainly based on multi-agent system (MAS) technology. MAS is an emerging field that evolved from the distributed computing and distributed artificial intelligence communities, it is being used in an increasingly wide variety of applications in power systems [8, 9].

In recent years, the MAS technique has been implemented by numerous researchers in various SPS service restoration problems [10-20]. A multi-agent system for automated service restoration of shipboard power systems was presented in [10]. It has been applied in AC radial SPS. In [11], the authors presented a MAS based approach for radial SPS service restoration. However, the MASs proposed in [10, 11] worked only for radial structured SPS restoration. In [12], the service restoration required global system information, so the self-healing restoration system was considered as a centralized system although the MAS was a decentralized structure. In [13-15], the authors designed a MAS for a simple radial distribution system and developed the interface between MAS and VTB simulation software. In [16, 17] the authors proposed a MAS composed of three different agents for ship system electric power restoration. By negotiating among agents without a control center, the system can perform restoration task according to the local information. In [18-20], the authors developed MAS based algorithms for reconfiguration of SPS, which was either mesh-structured AC distribution or ring-structured AC distribution. In summary, the SPSs used for the service restoration, in aforementioned literatures, were assumed to be radial or simplified ring structure.

In this paper, a novel service restoration approach for complex SPS is proposed based on multi-agent system. The rest of this paper is organized as follows. Section 2 describes brief descriptions of SPS. Section 3 improves the mathematical programming method proposed in [6, 7]. The next section provides brief introduction of multi-agent technology, and applies the proposed MAS to a complex SPS for service restoration. The validity and feasibility of proposed MAS is demonstrated by simulations in Section 4. Finally, conclusions are given in Section 5.

2. Shipboard power system

Consider a SPS model as shown in Fig.1. This system consists of four power stations, which are connected by tie-lines (TLs). The switchboard is connected to the generator of every station, which supplies power to power panels or to loads directly.

In this paper, all loads are classified as vital and non-vital loads. The vital loads connected to power panels or switchboards directly via ABT/MBTs. For vital loads, two
paths (normal and alternate) are provided to enhance the reliability of power supply, but only one of them is close at any time for the SPS need to operate in radial configuration. Graphical representation of this system is shown in Fig. 2.

![Fig. 2. Graphical representation of the SPS](image)

In Fig. 2, the node-edge graph described the topology of SPS, not considering physical elements. The nodes merely represent junctions in the SPS. Each ABT/MBT is represented with two edges. The edges in solid line indicate normal paths, and the ones in dotted line indicate alternate paths.

3. Mathematical problem formulation

In reference [6, 7], the problem is formulated as a network flow problem. Let $D_i (i=1, 2, ..., 60)$ represent the set of nodes and $B_j (j=1, 2, ..., 72)$ represent the set of edges in the Fig.2. Let $x_i$ represent the state of edge $B_i$ where $x_i = 1$ indicates $B_i$ is close and $x_i = 0$ indicates $B_i$ is open.

### 3.1 Objective function

In this paper, the objective function is to supply maximum number of the loads based on the priority, and minimize the number of branches which state has been changed in the restoration. The mathematical formulation of the objective function is shown below

![Equation 1](image)

where: $N_1$ – the number of vital loads, $N_2$ – the number of non-vital loads, $L_{i1}$ – the power of vital loads, $L_{i2}$ – the power of non-vital loads, $n_v$ – the number of branches that state need to change in the restoration scheme, $\lambda_1, \lambda_2, \lambda_3$ – coefficients, $z_i$ – power supply state of loads.

The priority weighting coefficients are calculated as follows:

![Equation 2](image)

where: $L_{2\text{max}}$ – the power of the largest non-vital load, $L_{2\text{min}}$ – the power of the least non-vital load, $L_{1\text{min}}$ – the power of the least vital load, $B_f$ – the total number of branches.

### 3.2 Constraints

a) Radial limits

The system should be operation in a radial structure. For the two path supply vital loads, only one edge can close

![Equation 3](image)

where: $x_i$ – the state of normal path, and $x_j$ – the state of alternate path.

b) Capacity constrains

The actual flow on an edge must not exceed the maximal capacity of the edge

![Equation 4](image)

where: $C_j$ – the maximal capacity of edge $B$, $y_i$ – the actual power flow of edge $B$.

c) Node constrains

The nodes could be classified as source node (such as $D_1, D_2$), intermediate node (such as $D_9, D_{25}$) and load node (such as $D_{25}, D_{28}$). Load nodes supply power to loads directly, and its injection power could be calculated as follows:

![Equation 5](image)

where: $L_i$ – the injection power of the load node; $z_i$ – power supply state of loads, $P_{iL}$ – the power of load $L_i$.

The intermediate nodes can be sorted as major network nodes and distribution network nodes. Major network nodes refer to four main switchboard nodes, which are $D_2, D_8$, respectively, distribution network nodes refer to intermediate nodes supplied from main switchboards, such as $D_9, D_{25}$. It is feasible to restrain the injection and outflow power of distribution network nodes according to Kirchoff’s current law, which postulates that the total injection power is equal to the total power outflow at any node.

![Equation 6](image)

where: $I$ – the branch set inflow into the node $i$; $O$ – the branch set outflow from node $i$. So for the nodes shown in Fig.3, equality constraint can be built according to Kirchoff’s current law: $y_1 = y_2 + y_3$.

![Fig. 3. Power flow of distribution network nodes](image)

In [6, 7], the authors think that the fault on any of the components in major network may not affect supply to any load, so this situation is not studied and the network of PSP is modified by merging all the generator switchboards and tie-lines. In this way the power flow of tie-lines is ignored, as a result, the real situation of the SPS cannot be obtained and the initial state of SPS cannot be reset. According to the actual situation, considering the reconfiguration of major network can supply flexible network structure, increase reliability of the SPS, and reduce the operation times of switches. Different from the distribution network, the direction of power flow in major network is uncertain, so the
node constrain based on Kirchhoff's current law is not applicable.

In this paper, we set a reference direction for power flow in the major network and give the equality constraints for the major network nodes $D_i$-$D_k$:

$$
\begin{align*}
 y_1 + y_8 &= y_5 + y_9 + y_{10} + y_{11} + y_{12} \\
 y_2 + y_3 &= y_6 + y_{13} + y_{14} + y_{15} + y_{16} \\
 y_3 + y_6 &= y_7 + y_{17} + y_{18} + y_{19} + y_{20} \\
 y_4 + y_7 &= y_8 + y_{21} + y_{22} + y_{23} + y_{24}
\end{align*}
$$

(7)

Due to the setting of reference direction, calculated value of power on the tie-lines may be negative, so tie-lines power should meet not only the formula (4) but also the inequality constraint as follows

$$
-C_{ij} \leq x_i y_i
$$

(8)

Moreover, the generators operating in parallel need to share loads according to its rated capacity respectively

$$
y_i y_j = \frac{y_j}{P_{Gi}}
$$

(9)

where: $y_i$, $y_j$ – the power output by generators $i$ and $j$; $P_{Gi}$, $P_{Gj}$ – the rated capacity of generators $i$ and $j$.

To satisfy the basic balance of power between generation and load, the edges connected with generator nodes need to meet active power constraint as follows:

$$
y_i x_i \leq P_{Gi}
$$

(10)

d) Major network open-loop constraint

In order to prevent major network operating in a ring structure, the tie-lines need to meet structure constraint as follows:

$$
\sum_{i \in H} x_i \leq m
$$

(11)

where: $H$ – the set of tie-lines, $m$ – the total number of tie-lines.

The optimizing software of LINGO 8.0 is employed to get optimized solution with branch and bound algorithm, after the completion of mathematical model.

4. Multi-agent system for SPS service restoration

4.1 Agent and multi-agent system

There is no precise definition of agent at present. Artificial intelligence (AI) researchers generally consider an agent as a form of entity with sensing, decision making, and actuation capabilities [21]. In this article, the agent is an information processor that performs autonomous actions based on information, so it is able to collect information, make effective decisions according to the sensory information, and execute the selected decision.

The MAS is an extension of agent technology where a group of loosely connected autonomous agents act in an environment to achieve a common goal [22]. MAS can be used to solve problems that are difficult or impossible for an individual agent or a monolithic system to solve. In MAS, every agent merely collects local information, while communicating with other agents to realize information sharing. The task could be divided into some smaller subtasks, assigned to different agents and completed under the collaboration among agents finally.

The proposed MAS in this paper is implemented based on JAVA agent development environment (JADE). The JADE, implemented in JAVA and meet the Foundation for Intelligent Physical Agents (FIPA) specifications, is a middleware for the development of multi-agent system. Each agent in JADE has a globally unique identity (AID) to distinguish from other agents. Agents exchange information in JADE by message passing. The JADE messages comply with agent communication language (ACL) standard. An ACL message has several important attributes such as sender, receiver, content, conversation ID and so on. The conversation ID is set to help agent to understand the purpose of messages received.

4.2 The architecture of MAS

In this article, peer to peer architecture is used to design the MAS for SPS restoration. For each power station, we set a zone agent (ZA) to manage all the components of the area. Each ZA is able to communicate with any other ZAs and has the ability to collect information, analyze data and make decisions independently. The architecture of MAS is shown in Fig. 4.

As Fig. 4 shows, the system is divided into 3 layers: the physical layer, the communication layer and the MAS layer. The physical layer corresponds to the actual shipboard power system. The MAS layer is comprised of 4 ZAs to manage the SPS autonomously. The communication layer is used for the data transmission between the physical layer and the MAS layer. Every ZA collects information of the related power station, analyzes data and makes decisions independently. In this way, each power station could be independent and self-government. If the fault can be handled by the ZA of the fault area independently, the all work of information collecting and processing would be carried out only in the fault area, while the other ZAs would not be affected. Otherwise, the ZA of the fault area need to communicate with the others and complete the restoration work together.

4.3 The restoration rules

When a fault occurs, the measures taken for service restoration of loads in SPS are limited. All the possible operation schemes of ZA0 in service restoration are listed in Tab.1. In this paper, the load transfer between power stations during service restoration is regarded as power transfer, so the final result of restoration is to achieve power balance in the SPS.

<table>
<thead>
<tr>
<th>Plan</th>
<th>content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Close TL0 6 L1 transfer to ZA3, L5 transfer to ZA1</td>
</tr>
<tr>
<td>2</td>
<td>Close TL3 7 L1, L3 transfer to ZA3</td>
</tr>
<tr>
<td>3</td>
<td>L1 transfer to ZA3 8 L5 transfer to ZA1, L3 transfer to ZA3</td>
</tr>
<tr>
<td>4</td>
<td>L5 transfer to ZA1 9 L1, L3 transfer to ZA3, L5 transfer to ZA1</td>
</tr>
<tr>
<td>5</td>
<td>L3 transfer to ZA3 10 Load shedding</td>
</tr>
</tbody>
</table>

Fig.4. Architecture of MAS

**Table 1. The restoration plan list of ZA0**
Let $P_e$ represent the maximum power provided by the generator, $P_L$ represent all the load power, $P_n$ represent the net power of the area. The $P_n$ can be calculated as follows:

$$P_n = P_e - P_L$$

where: $P_e$ being positive represents the power supply of the area is sufficient, $P_L$ being negative represents there is power shortage in the area.

Let $P_{in}$ represent the power transferred from other areas, and $P_{out}$ represent the power ZA deciding to transfer out. When $P_{in} \leq P_n$, the area is able to absorb the power transferred from other areas. When $P_{in} > P_n$, the power transferred from other areas will lead to power imbalance in the area, and then it is necessary for ZA to take measures to meet the power balance constraint. In order to minimize the operation times, closing the tie-lines will be the prior consideration. To prevent the power transferring into circulation, ZA must meet the constraint as follows when making decisions

$$P_{in} \geq P_{out}$$

If the power balance constraint could not be met and there is no way to transfer loads, ZA will take measures to shed load until meeting the constraint. This article proposes five types of messages for the ZAs to communicate with each other as indicated by Table 2.

<table>
<thead>
<tr>
<th>Type</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault</td>
<td>The fault information</td>
</tr>
<tr>
<td>Query</td>
<td>Query the state information of TLs that in other areas and the alternate paths of the loads in this area</td>
</tr>
<tr>
<td>Reply</td>
<td>Provide the TLs and alternate paths information</td>
</tr>
<tr>
<td>Told</td>
<td>Release the major network information to other ZAs</td>
</tr>
<tr>
<td>Action</td>
<td>Execute the program that made by ZA</td>
</tr>
</tbody>
</table>

The flow chart of ZA program is shown in Fig. 5. After initialized, ZA turns to wait state. If receiving message, the ZA will be activated to analyze the message and make decision, otherwise, it will keep waiting.

Because the $P_n$ value of every area are related to the major network structure, the state information of all TLs is necessary for each ZA to calculate the $P_n$ value. After fault occurred, the ZA of the fault area will send query messages to the others to collect the TLs information. Then it will release the major network information to the other ZAs for calculation of $P_n$ value.

The primary principle of ZA is to ensure the power supply of these high priority loads at first, and then to try to avoid large loss of power. The flowchart of load shedding, as shown in Fig. 6, describes the process in detail.

![Fig. 6. Flow chart of load shedding](image)

5. Result

The parameters of the test shipboard power system are shown in Table 3. The “(1)“ means the load is a vital load while the “(2)“ means the load is a non-vital load.

<table>
<thead>
<tr>
<th>Component</th>
<th>Power [kW]</th>
<th>Component</th>
<th>Power [kW]</th>
<th>Component</th>
<th>Power [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>G0</td>
<td>840</td>
<td>L5(1)</td>
<td>160</td>
<td>L13(1)</td>
<td>110</td>
</tr>
<tr>
<td>G1</td>
<td>880</td>
<td>L6(1)</td>
<td>100</td>
<td>L14(2)</td>
<td>72</td>
</tr>
<tr>
<td>G2</td>
<td>838</td>
<td>L7(2)</td>
<td>80</td>
<td>L15(1)</td>
<td>67</td>
</tr>
<tr>
<td>G3</td>
<td>840</td>
<td>L8(1)</td>
<td>325</td>
<td>L16(1)</td>
<td>100</td>
</tr>
<tr>
<td>L1(1)</td>
<td>70</td>
<td>L9(2)</td>
<td>185</td>
<td>L17(1)</td>
<td>205</td>
</tr>
<tr>
<td>L2(2)</td>
<td>120</td>
<td>L10(1)</td>
<td>44</td>
<td>L18(2)</td>
<td>200</td>
</tr>
<tr>
<td>L3(1)</td>
<td>200</td>
<td>L11(1)</td>
<td>225</td>
<td>L19(2)</td>
<td>165</td>
</tr>
<tr>
<td>L4(2)</td>
<td>150</td>
<td>L12(2)</td>
<td>205</td>
<td>L20(1)</td>
<td>30</td>
</tr>
</tbody>
</table>

In order to verify the validity of the proposed method, a large number of simulations have been done under different fault conditions. For space considerations, here we only demonstrate two typical examples.

5.1 Case 1

Assuming all the power stations operate independently, there are two faults occurred at the same time on the edges 34 and 38. After the faults, L6 and L8 lose power. Meanwhile the TL0 and TL3 have been damaged and can not close. The communication process of ZAs is shown in Fig. 7.

![Fig. 7. Communication process of ZAs](image)

In Fig. 7, the FA is a special agent which will send messages to ZA to provide fault information. In the initial state, the $P_n$ value of every area is respectively 140, 146, 139 and 140 kW. The process of the decision-making between each ZA is shown in Table 4.
The results of integer programming method introduced in section are shown in Table 5. It is clear that the solutions are the same as those obtained by the MAS method this paper proposed. In order to compare the two methods particularly, a large number of simulations have been carried out. We set 8 fault cases for each area, and get 32 simulation results. It is noted that 99.2% results of the two methods are same. Only in one case, there is tiny difference between the two methods. In that case, the two methods select different TLs respectively to restore the power supply for all loads.

### Table 4. Process of the decision-making for case 1

<table>
<thead>
<tr>
<th>Message</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Message 1</td>
<td>FA sends fault information to ZA1. As the L6 and L8 lose power, the $P_r$ value of ZA1 updates to 571 kW.</td>
</tr>
<tr>
<td>Message 2</td>
<td>ZA1 queries ZA0 for the state information of TL0.</td>
</tr>
<tr>
<td>Message 3</td>
<td>ZA1 queries ZA2 for the state information of TL2.</td>
</tr>
<tr>
<td>Message 4</td>
<td>ZA2 queries ZA3 for the state information of TL3.</td>
</tr>
<tr>
<td>Message 5</td>
<td>ZA2 provides the state information of TL2 to ZA1.</td>
</tr>
<tr>
<td>Message 6</td>
<td>ZA0 provides the state information of TL0 to ZA1.</td>
</tr>
<tr>
<td>Message 7</td>
<td>ZA3 provides the state information of TL3 to ZA1. ZA1 releases the major network information to the other ZAs after collecting all the TLs state information.</td>
</tr>
<tr>
<td>Message 8</td>
<td>ZA1 sends the major network information to ZA0.</td>
</tr>
<tr>
<td>Message 9</td>
<td>ZA1 sends the major network information to ZA2.</td>
</tr>
<tr>
<td>Message 10</td>
<td>ZA2 sends the major network information to ZA3. All the ZAs recalculate the $P_r$ value according to the major network information.</td>
</tr>
<tr>
<td>Message 11</td>
<td>ZA1 transfers the L6 and L8 to ZA0 by the alternate path. After accepting the L6 and L8, the $P_r$ value of ZA0 updates to -285 kW. Then ZA0 decides to transfer L3 and L5 to meet the power balance constraint.</td>
</tr>
<tr>
<td>Message 12</td>
<td>ZA0 transfers the L5 to ZA1 by the alternate path. The $P_r$ value of ZA1 updates to 411 kW.</td>
</tr>
<tr>
<td>Message 13</td>
<td>ZA0 transfers the L3 to ZA3 by the alternate path. Then the $P_r$ value of ZA3 updates to 75 kW, and the $P_r$ value of ZA3 updates to -60 kW after accepting the L3. ZA3 decides to close the TL2 to meet the power balance constraint.</td>
</tr>
<tr>
<td>Message 14</td>
<td>After ZA3 closed the TL2, ZA2 shares 60 kW load from ZA3. The $P_r$ value of ZA2 updates to 79 kW. The restoration process is completed, and then all the loads get power supply.</td>
</tr>
</tbody>
</table>

### Table 5. Process of the decision-making for case 2

<table>
<thead>
<tr>
<th>Message</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Message 1</td>
<td>The process from message 1 to message 10 is same to the case 1. In case 2, the L7 and L9 are both non-vital loads, and they could not be restored once lost of power.</td>
</tr>
<tr>
<td>Message 10</td>
<td>ZA1 transfers the L6 and L8 to ZA0 by the alternate path. After accepting the L6 and L8, the $P_r$ value of ZA0 updates to -285 kW. Then ZA0 decides to close TL3.</td>
</tr>
<tr>
<td>Message 11</td>
<td>ZA1 transfers the L10 to ZA2 by the alternate path. After accepting the L10, the $P_r$ value of ZA2 updates to 95 kW.</td>
</tr>
<tr>
<td>Message 12</td>
<td>ZA2 closes the TL2. Then ZA2 shares 145 kW load from ZA0, and the $P_r$ value of ZA2 updates to -145 kW, so it decides to close TL2.</td>
</tr>
<tr>
<td>Message 13</td>
<td>The TL3 is closed. Then ZA3 shares 285 kW load from ZA0, and the $P_r$ value of ZA3 updates to -145 kW, so it decides to close TL2.</td>
</tr>
<tr>
<td>Message 14</td>
<td>The TL3 is closed. Then ZA2 shares 145 kW load from ZA3. The $P_r$ value of ZA2 updates to -50 kW. At last, ZA2 decides to shed the normal load L14 to meet the constraint. The restoration process is completed, and all vital loads get power supply.</td>
</tr>
</tbody>
</table>

### Table 6. Fault restoration results of integer programming method

<table>
<thead>
<tr>
<th>The fault</th>
<th>Restoration plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>L3 is transferred to ZA3; L5 is transferred to ZA1; L6 and L8 are transferred to ZA0; TL2 is closed</td>
</tr>
<tr>
<td>Case 2</td>
<td>L6 and L8 are transferred to ZA0; L10 is transferred to ZA2; L7 and L9 lose power; TL2 and TL3 are closed; L14 is shed</td>
</tr>
</tbody>
</table>

From the results, it is proven that the proposed multi-agent system is able to find an optimal or a sub-optimal target configuration in all cases. The solutions are the same as those obtained by the mathematical programming approach. The average simulation time of MAS method is 1ms. In fact, the real time is far less than that, but the minimum time scale of the development software is 1ms. For the same test system, the average simulation time of the fastest discrete particle swarm optimization algorithm proposed in [3] is 14 ms, and the average simulation time of the integer programming method is 1s. Obviously, the MAS method proposed above is dominant in the time of decision making, which is important for ship power system especially in the combat environment.
6. Conclusion

This paper proposes multi-agent system approach for shipboard power system restoration. Consisting of four zone agents, the MAS is able to decide the target configuration and the switching sequence. The validity and effectiveness of the proposed multi-agent system have been demonstrated by applying it to a complex shipboard power system. It is indicated that, the MAS technique can increase survivability and reliability of shipboard power system, and moreover has a distinct advantage in computing time compared with traditional restoration methods. Future work should be directed to improve the architecture of MAS and restoration rules for more complex SPS.

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