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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 doi stanu sprzed uszkodzenia jak najszybciej. W artykule zaproponowano ulepszoną metodę wykorzystująca 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, przywracania 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 □ provides brief descriptions of SPS. Section □ 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 □. Finally, conclusions are given in section □.

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 supplys power to power panels or to loads directly.

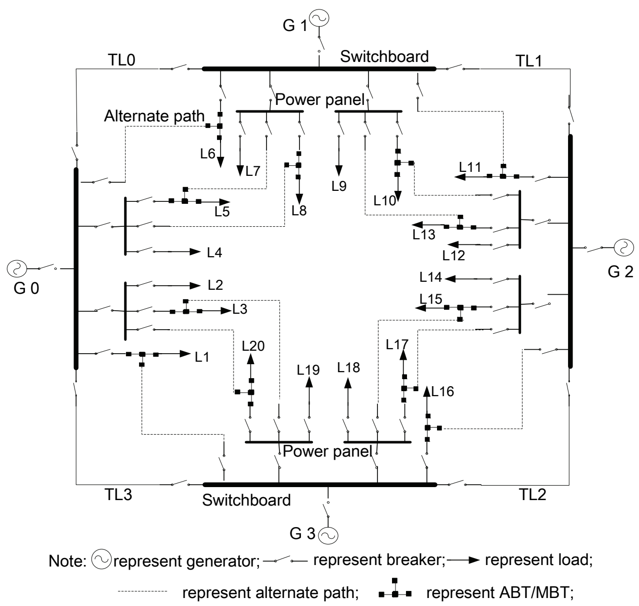

Fig.1. Simplified shipboard power system

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.

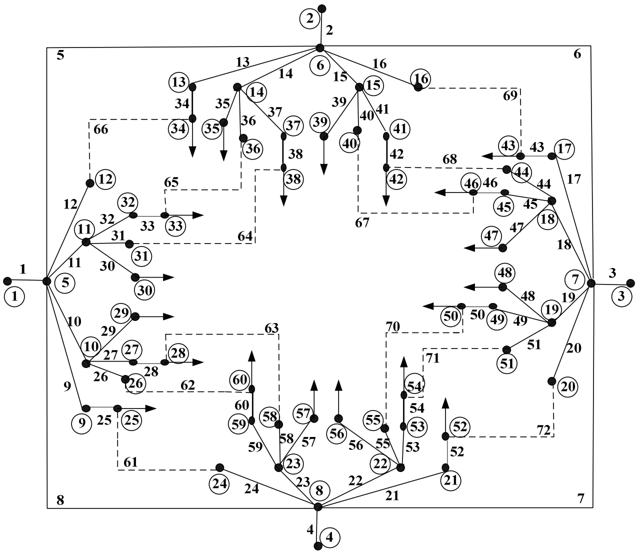

Fig.2. Graphical representation of the SPS

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_i (i=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

$$\max\ (\lambda_1 \sum_{i=1}^{N_1} z_i L_{1i} + \lambda_2 \sum_{i=1}^{N_2} z_i L_{2i} - \lambda_3 n_v) \tag{1}$$

where: N_1 – the number of vital loads, N_2 – the number of non-vital loads, L_{1i} – the power of vital loads, L_{2i} – the power of non-vital loads, n_v – the number of branches that state need to change in the restoration scheme, λ_1, λ_2, λ_3 – coefficients, z_i – power supply state of loads.

The priority weighting coefficients are calculated as follows:

$$\begin{cases} \lambda_1 = \dfrac{\lambda_2 L_{2\max}}{L_{1\min}} \\ \lambda_2 = 1 \\ \lambda_3 = \dfrac{\lambda_2 L_{2\min}}{B_f} \end{cases} \tag{2}$$

where: $L_{2\max}$ – the power of the largest non-vital load, $L_{2\min}$ – the power of the least non-vital load, $L_{1\min}$ – 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

$$x_i + x_j \le 1 \tag{3}$$

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

$$x_i y_i \le C_i \tag{4}$$

where: C_i – the maximal capacity of edge B_i, y_i – the actual power flow of edge B_i.

c) Node constrains

The nodes could be classified as source node (such as D_1, D_2), intermediate node (such as D_5, D_6) 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:

$$L_i - z_i P_{Li} = 0 \tag{5}$$

where: L_i – the injection power of the load node; z_i – power supply state of loads, P_{Li} – 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_5-D_8 respectively, distribution network nodes refer to intermediate nodes supplied from main switchboards, such as D_9 and D_{10}. It is feasible to restrain the injection and outflow power of distribution network nodes according to Kirchhoff's current law, which postulates that the total injection power is equal to the total power outflow at any node.

$$\sum_{i\in I} y_i = \sum_{j\in O} y_j \tag{6}$$

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 Kirchhoff's current law: $y_1 = y_2 + y_3$.

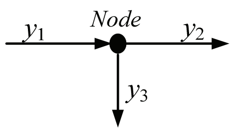

Fig.3. Power flow of distribution network nodes

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_5-D_8.

$$(7)\qquad \begin{cases} y_1 + y_8 = y_5 + y_9 + y_{10} + y_{11} + y_{12} \\ y_2 + y_5 = y_6 + y_{13} + y_{14} + y_{15} + y_{16} \\ y_3 + y_6 = y_7 + y_{17} + y_{18} + y_{19} + y_{20} \\ y_4 + y_7 = y_8 + y_{21} + y_{22} + y_{23} + y_{24} \end{cases}$$

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

$$(8)\qquad -C_i \le x_i y_i$$

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

$$(9)\qquad \frac{y_i}{P_{Gi}} = \frac{y_j}{P_{Gj}}$$

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:

$$(10)\qquad y_i x_i \le P_{Gi}$$

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:

$$(11)\qquad \sum_{i \in H} x_i \le m$$

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.

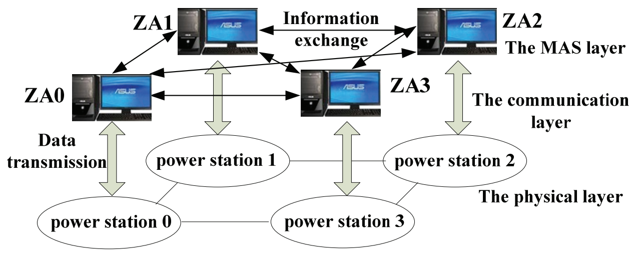

Fig.4. Architecture of MAS

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 1. The restoration plan list of ZA0

plan	content	plan	content
1	Close TL0	6	L1 transfer to ZA3, L5 transfer to ZA1
2	Close TL3	7	L1, L3 transfer to ZA3
3	L1 transfer to ZA3	8	L5 transfer to ZA1, L3 transfer to ZA3
4	L5 transfer to ZA1	9	L1, L3 transfer to ZA3, L5 transfer to ZA1
5	L3 transfer to ZA3	10	Load shedding

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:

(12) $$P_n = P_e - P_l$$

where: P_n being positive represents the power supply of the area is sufficient, P_n 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 $P_{in} \le P_n$, 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

(13) $$P_{in} \ge P_{out}$$

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 2. Types and content of the message

Type	Content
Fault	The fault information
Query	Query the state information of TLs that in other areas and the alternate paths of the loads in this area
Reply	Provide the TLs and alternate paths information
Told	Release the major network information to other ZAs
Action	Executive the program that made by ZA

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.

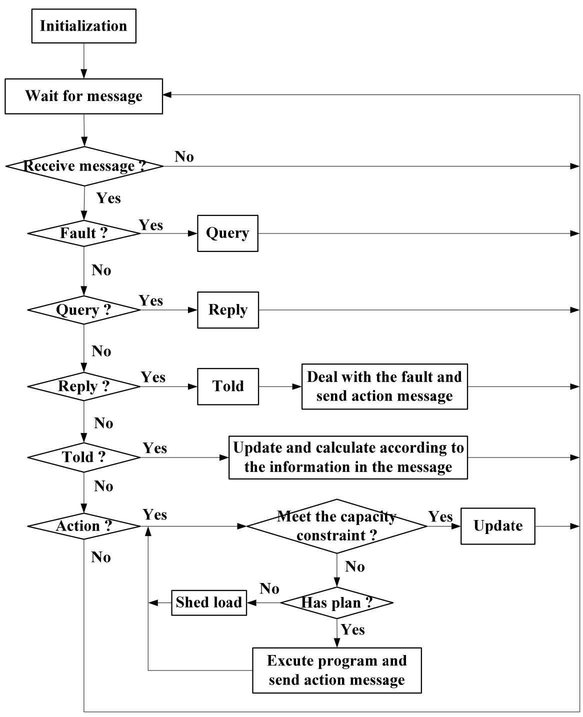

Fig.5. Flow chart of Agent program

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.

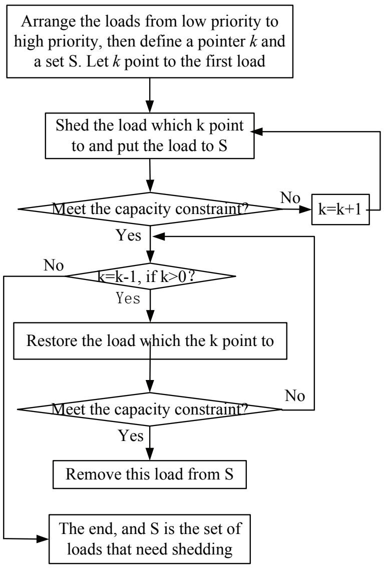

Fig.6. Flow chart of load shedding

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 3. The parameters of the system

Component	Power [kW]	Component	Power [kW]	Component	Power [kW]
G0	840	L5(1)	160	L13(1)	110
G1	880	L6(1)	100	L14(2)	72
G2	838	L7(2)	80	L15(1)	87
G3	840	L8(1)	325	L16(1)	100
L1(1)	70	L9(2)	185	L17(1)	205
L2(2)	120	L10(1)	44	L18(2)	200
L3(1)	200	L11(1)	225	L19(2)	165
L4(2)	150	L12(2)	205	L20(1)	30

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.

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.

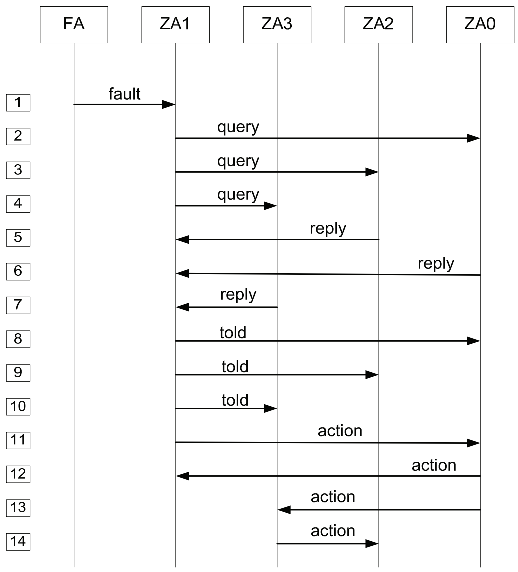

Fig.7. Communication information of MAS

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

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

5.1 Case 2

Assume there is a fault occurring on the main switchboard in area 1. Due to the fault, all the loads in this area are lost of power. The communication process of ZAs is shown in Fig. 8, and the process of the decision-making between each ZA is shown in Table 5.

The restoration results of integer programming method introduced in section □ are shown in Table 6. 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.

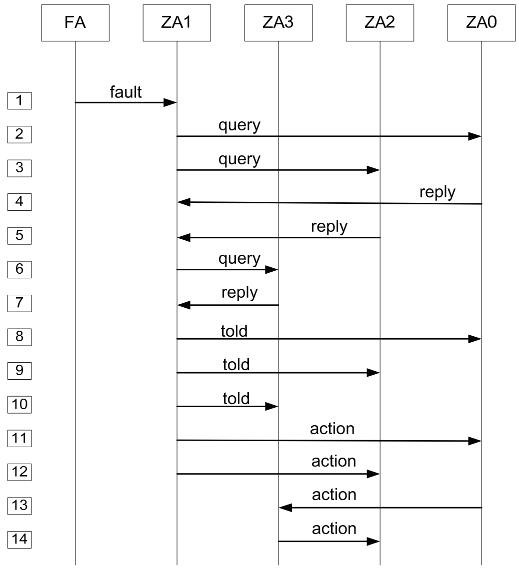

Fig.8. Communication information of MAS

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

Message 1 …… Message 10	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.
Message 11	ZA1 transfers the L6 and L8 to ZA0 by the alternate path. After accepting the L6 and L8, the P_n value of ZA0 updates to -285 kW. Then ZA0 decides to close TL3.
Message 12	ZA1 transfers the L10 to ZA2 by the alternate path. After accepting the L10, the P_n value of ZA2 updates to 95 kW.
Message 13	The TL3 is closed. Then ZA3 shares 285kW load from ZA0, and the P_n value of ZA3 updates to -145 kW, so it decides to close TL2.
Message 14	The TL2 is closed. Then ZA2 shares 145kW load from ZA3. The P_n value of ZA2 updates to -50kW. 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.

Table 6. Fault restoration results of integer programming method

The fault	Restoration plan
Case 1	L3 is transferred to ZA3; L5 is transferred to ZA1; L6 and L8 are transferred to ZA0; TL2 is closed
Case 2	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

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 14ms, 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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