

Framework for Multi-Agent System (MAS) Detection and Control of Arcing of Shipboard Electric Power Systems

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Abstract—The focus of this paper is the development of a Multi-agent System (MAS) for detection and diagnosis of arcing faults in the shipboard electric power systems. Also provided is fault management via scheduling to maintain shipboard power system operation. The control schemes in the MAS framework are based on optimization methods and rule-based techniques. A prototype framework for implementation has been developed and tested on an Integrated Power System (IPS).

Index Terms—Multi-agent System (MAS), arcing fault, framework

I. INTRODUCTION

Electric shipboard power systems provide the vessel with the necessary power to maintain its operation. The Navy system is a highly intricate network of various generators, back up power, power cables, AC and DC loads, and various converters to generate, transmit and supply power at different voltage levels. It is, like all other equipment or networks, prone to possibility of failure in service due to faults.

The Integrated Power System (IPS) includes propulsion, ship's service power generation, distribution and conversion [1]. Its structure includes both software and hardware components and provides electric power to the ship for various loads such as weapons and defense systems and propulsion. It is highly coupled and has a high level of control through the use of power electronic system [2].

The main components of this system are the AC power generators, synchronous loads, propulsion loads, and various power converters. The converters are AC/DC Rectifier units, DC/DC converters or Ship Service Converter Module (SSCM) and DC-AC also referred to as the Ship Service Inverter Module (SSIM). Also, the system supports various loads such as motor controllers, and propulsion, pulse, induction motor, constant power loads, and miscellaneous components.

The system is rated at 40 MW, 4,160VAC (3-phase, 60Hz) generating capacity supplied by 2 units and the DC port (or starboard) distribution bus operates at a maximum 1,000VDC. SSCM steps down this voltage from 800VDC to various power levels (440VAC at 60Hz, 440VA at 400Hz, and 500V DC).

The DC sub-system is divided into three different zones, as shown in Figure 1, each zone serving a particular load type: Zone 1 contains fixed AC loads while variable speed controlled loads and motor controlled loads can be found in

zone 2. Zone 3 is reserved for the constant power (DC power) loads.

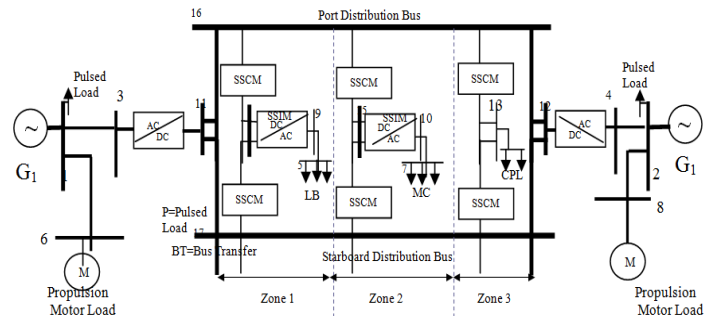


Fig.1. Structure of the Navy Integrated Power System (IPS) Benchmark

A Multi-agent System (MAS) is utilized as detection and diagnosis device and the system is monitored for arcing fault signatures before further damage can take place. As a result, there is an increase in the efficiency of the network as the possibility of undetected faults is minimized. [4] introduces the unified model language and genetic algorithm for the control of distributed power system. [3] uses spanning tree protocol LEAP with JADE for shipboard power system reconfiguration.

II. FORMULATION OF PROBLEM

The primary goal is to minimize the disruption of the ship power system caused by arc faults by maintaining service to as many loads in the system as possible. Following arcing fault diagnosis and detection on ship systems, a Severity Index is formulated to determine the severity of the fault and the extent to which it stresses the network. This is done by first calculating the base case power flows within the system under no arcing conditions. After an arc fault has been initiated, the power system is checked once again and during this check, the severity of the fault is determined. Control actions will be determined within this MAS framework, based on the calculated index. Post-control evaluation of the system is also conducted in order to verify whether the index has been reduced which would indicate that the arc fault has been handled.

A. Severity Analysis

The severity analysis is implemented based on the calculation of Severity Index (SI). The SI is a tool used to assess the level of stress to the system associated with the detected fault. The parameters for the severity analysis that were used are categorized in 3 groups: X , M , and E where X represents the network parameters such as bus voltages and line current values. M is the measured parameter set, which includes the values of the physical components such as temperature levels of converters and generators. The parameters of E correspond to the external parameters like arc power. The parameter set are given as:

$$\begin{aligned} X &= \{\text{Voltage, line power}\} \\ M &= \{\text{Temperature, Basic Insulation Level}\} \\ E &= \{\text{Arc Power, Current}\} \end{aligned}$$

Each state is assigned a weight to determine the dominant state and corresponding parameter that contributes most to the fault condition. Since this weight is not initially known, an objective function has been used to find the weight vector that would maximize or minimize the SI. The formulation is given as shown in equations (1) and (2).

$$\max \text{ or } \min \quad f(\omega) = \sum_{i=1}^3 \omega_i U_i = SI \quad (1)$$

(where $U_1=X$, $U_2=M$ and $U_3=E$)

$$U_i = \{u_1, \dots, u_n\}, \text{ and } 1 \leq j \leq n$$

$$\text{where } U_i = \left\{ \begin{array}{l} \frac{|u_j - u_j^{\min}|}{u_j^{\max}} \text{ for } u_j < u_j^{\min} \\ \frac{|u_j - u_j^{\max}|}{u_j^{\max}} \text{ for } u_j > u_j^{\max} \end{array} \right\} \quad (2)$$

$$\text{s.t. } \sum_{i=1}^3 \omega_i = 1, \text{ and } \omega_i \geq 0$$

where, ω is the weighting factor, u_j is the parameter set for X , M , and E in specific state of the system and i is index for parameter state, j is index for individual parameter and $u^{\min/\max}$ is min/max limit of individual parameters.

Both the maximum and minimum parameter limits are used because if only the upper limit was used to indicate violations, there may be cases where the lower limit violations will go undetected. Hence, the two limit violations are taken into account using u_{\min} and u_{\max} in equation (2). When the range of SI is obtained, along with the weight ω that has the most impact, the corresponding parameter would be indicated as the most detrimental. This result would then be sent to the Scheduling Agent to schedule an action to handle this particular violation.

Both the minimum and maximum SI was found so that a range could be obtained whereby the least severe and most severe values can be achieved. After the action has been implemented, the system should be re-checked for violations and the new SI recalculated and compared.

B. Arc Fault Analysis

For this analysis a 3-phase fault high impedance arc that occurs intermittently across a small air gap existing between an energized conductor and the hull of the ship is analyzed. Numerous methods were investigated which include the Long Arc[6], Physics Approach[7], Stochastic Approach[8], Network Impedance and High Impedance[9] methods. The method implemented in this work is the Physics Method which depends on several factors like spark gap, voltage levels and arc independence. It allows for determination of the fault, whose insufficient and variable current magnitude makes it difficult to detect by conventional means. The arc voltage can be denoted as a function of the arc current as follows:

$$V_{k,arc} = (20 + 534g)I_{arc}^{0.12} \quad (3)$$

where, $V_{k,arc}$ is the arc voltage at bus k , g is the width of arc gap in meters and I_{arc} is the arc current.

Similarly, the arc power can be expressed as:

$$P_{arc} = V_{arc} \times I_{arc} \quad (4)$$

Once the arc model is completed and corresponding values are stored in the MAS database. Bus voltages and line flows are observed from the network and checked to verify whether the values are in the required limits of $0.9 < V_k < 1.1 p.u.$ for voltage and $P_{ij} < 1.4 p.u.$ for real power flows.

For this analysis violations of both the upper and lower limits are considered and quantified by the Severity Index which used by the MAS to decide the proper action to follow to maintain service to loads and minimize disruption of the system caused by the indicated severe arc.

III. DESIGN OF THE FRAMEWORK FOR THE MAS FOR ARCING FAULT DETECTION

The multi-agent based system (MAS) framework introduced provides a tool for effectively detecting the fault speedily and providing the diagnosis necessary to ensure maximum load accommodation for post fault conditions.

The overall framework has the following decision characteristics:

- i. A system architecture which contains the topology of the system and its environment.
- ii. An analysis scheme, whereby a parameter database is obtained by the use of the power flow and arcing methods.
- iii. A MAS system which coordinates the processing of the analysis data back to the scheduler.
- iv. Deterministic rules ensure that an optimal scheduler is attained and communicated back to the architecture.

Various components of the ship are represented by the several agents that work and communicate with each other to maintain the serviceability of the ship as depicted in Figure 2. The framework presents the agent architecture which features the process from the user interface to the communication modules along with the functions inherent in each agent is displayed. The bold arrows indicate the communication channel where the interactions and messages among the agents can be made through the use of the specified language. The

dashed arrows indicate the database channel which will facilitate the data acquisition process as it connects the individual agent databases with the user interface data. The thin black line represents the remainder of the generic inter-agent communication which provides the interactions for the respective engines and the coordination of the assigned goals.

The MAS consists of six agents: an Arbitrator Agent (AA), a System Monitoring Agent (SMA), a Fault Detection Agent (FDA), a Diagnosis Agent (DA), a Judgment Index Agent (JIA), and a Scheduling Agent (SA). Each of these agents is assigned a unique ID and is restricted to communicate only within their environment to ensure a decentralized system.

This overall MAS design can be observed where the SMA is responsible for checking the states of the system and informing the FDA of any events that has been monitored. The FDA then classifies the event according to class, type and location of fault where necessary. Subsequently, the fault information is passed to the DA which then can interpret the fault. The JIA is then informed of its diagnosis of the fault and decides how the fault should be handled. The SA receives the judgment ordered from the JIA and is then required to schedule the appropriate action for the Arbitrator to implement. When implemented, the process repeats itself to constantly monitor the system for occurring faults so that management of the dangerous fault can be done instantaneously.

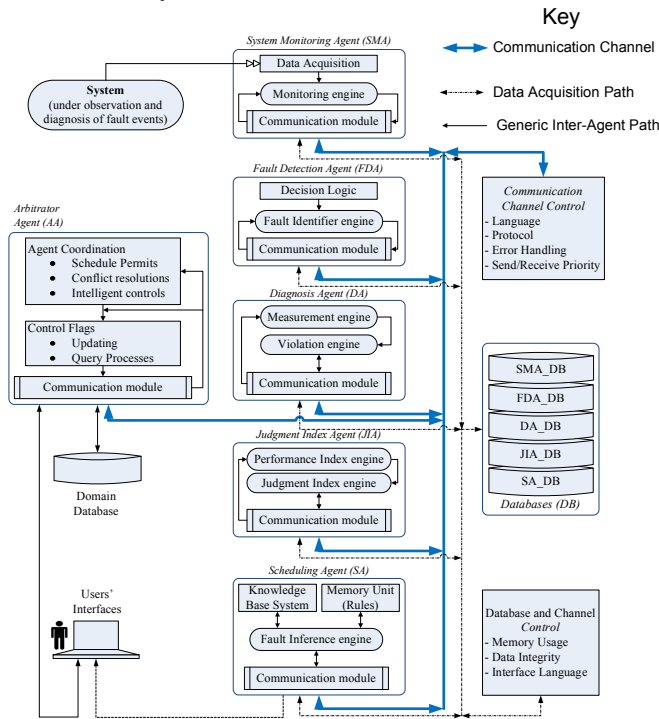


Fig.2. MAS Framework

A. Agent Integration

The agent integration steps are listed below:

Step 1: AA reads state information i.e. power flow, arcing temperature and loads parameter limits.

Step 2: SMA receives state information and checks for abnormal event.

If event is abnormal
Then send event to FDA.

Else send message to AA system is o.k. and get updated state information and repeat from step 2.

Step 3: FDA receives event information and classifies data as fault.

If event is fault

Then send to DA.

Else indicate that abnormal event can be normal.

Step 4: FDA sends fault record to DA.

Step 5: DA receives fault record and requests limits data from AA.

Step 6: DA compares measured fault record with data limits and indicates violated limits.

If $U > U^{\max}$

Then indicate limit violation and send to JIA.

Else fault record is not severe and can be ignored.

Step 7: DA send violated fault record to JIA.

Step 8: JIA receives fault record violations and requests performance index data.

Step 9: JIA calculates the severity index of the fault records:

If weights are loaded

And state dependences are known

And rank metric is loaded

Then indicate dominant parameter.

And reorder fault records according to dominance

Else do nothing.

Step 10: JIA sends order of judgment to SA.

Step 11: SA receives judgment from JIA and SA calls Knowledge Base to begin firing of rules.

Step 12: Based on rule fired SA schedules action to take and sends action to AA.

Step 13: AA receives action and informs operator of action to take.

Step 14: Operator implements action and updated system state information is sent to AA.

Step 15: Repeat from Step 1.

B. Rule-base for Agents

There are a set of deterministic rules utilized to carry out the actions of the particular agents which ensure an optimal scheduler. A selection of this rule-base as defined within the corresponding agents is detailed in Table 1.

Table. 1 Sample Rule-base for the MAS Agents

Agent	Rule Names	Description
SMA	SMA_1	If $\{X \cap M \cap E\}$ are checked Then send parameter values to FDA.
	SMA_2	If operation state has been received from SA Then display that state.
FDA	FDA_1	Check of values of I_a , I_b and I_c to classify fault by comparison to table for Class, Type and Location
Agent	Rule Names	Description
DA	DA_1	Check of the measurements, S with X, M and E to classify inputs as electrical, arc or physical

		measurements.	
	DA_2	Check for electrical network limit violation	
	DA_3	Check for physical limit violation	
DA	DA_4	Check for external limit violation	
	DA_5, DA_6, DA_7	Check weights and fault severity	
	JIA	JIA_2	Check for determination of violations in any state.

IV. RESULTS AND DISCUSSION OF THE IMPLEMENTATION SCHEME

The model of the ship system used is a reduced version of the actual Navy integrated power system which still has the key loading and converter components to represent the original model due to the several redundancies and the symmetrical nature of the system. To generate the live currents and bus voltage data, the power flow was calculated using the backward/forward sweep method. Due to the mixed AC and DC make up of the network and the presence of various load and converter components; a modified power flow method was used to adequately represent the converters and loads in the network.

For the computational tools used, it is beneficial to note that while rules can be used to provide a knowledge base for the agents, a hybrid scheme incorporating optimization would yield faster more optimal results.

The results represent the analysis of a MAS Framework implementation scheme that incorporates two important sub modules, namely, (i) the analysis of the system via power flow and arcing, and (ii) the integration of the analysis with the agents. The analysis of the results will be extended in two key directions for future advanced work that is aimed at increasing the efficiency of the design. These areas of research are (1) Building of the complete framework in JADE and (2) Hardware integration to ensure real time data acquisition.

The integration of the analysis is described using the events that trigger the agents to act and the scenarios that the agents will undertake given the examples in the cases presented previously. Figure 3 gives the integration of the Base Case Scenario 1. The data associated with each package is given as listed next:

- Data package 1: Network Data $P, Q, V, \theta, T_g = 50$
- Data package 2: Fault Description
- Data package 3: $CTL = 0$ (Class, Type and Location of fault)
- Data package 4:
 $40^\circ\text{C} < 50 < 135^\circ\text{C}$, hence no violation;
 $0.9 < \text{all bus voltages} < 1.1$ hence, no violation
- Data package 5: No violation. AA is messaged "Take no Action"

For Scenario 2, the post fault analysis case is used to show the agent integration. The Figure 3 illustrates the interaction for this case.

The data package corresponding to each package is as follows:

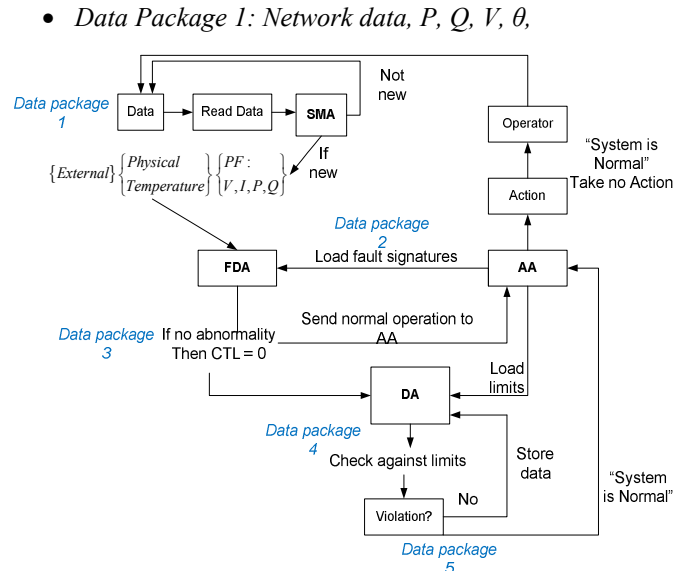


Fig.3. Agent Integration for Scenario 1

- Data Package 1: Network data, P, Q, V, θ ,
- Data Package 2: $T_g, T_{XM} = 150, BIL = 61.051,$
 $I_g = 4.2, I_{CON} = 1.2$
- Data Package 3:
 $I_{sc} = 5555.1A, V_{arc} = 520.87V, Z_{arc} = 0.105 p.u.$
 $I_{arc} = 2226.0528A, P_{arc} = 1159.482kW$
- Data Package 4: Fault Description
- Data Package 5: Impact on power flow due to arc at bus 2
- Data Package 6: $CTL = 3$ (Class, Type and Location of fault)
- Data Package 7: Parameter limits
- Data Package 8:
 $150 > 135^\circ\text{C}$, hence T_g and TXM are violations
 $4.2 > 2.5$ hence, I_g limit is violated
- Data Package 9: SI range $[0.6111, 1.0706]$
- Data Package 11: Knowledge base
- Data Package 12: Fire rules:
1. B1 (system has violation and actions are available)
2. B4 (Schedule actions based on order of control options.)
- Data Package 13: Options:
- Load shedding at Bus 2 (0.5 + 0.05 j)
- Isolation of fault bus 2
- Isolation of fault bus 2
- Data Package 14: 1st option "Shed Load" (0.5 + 0.05j)

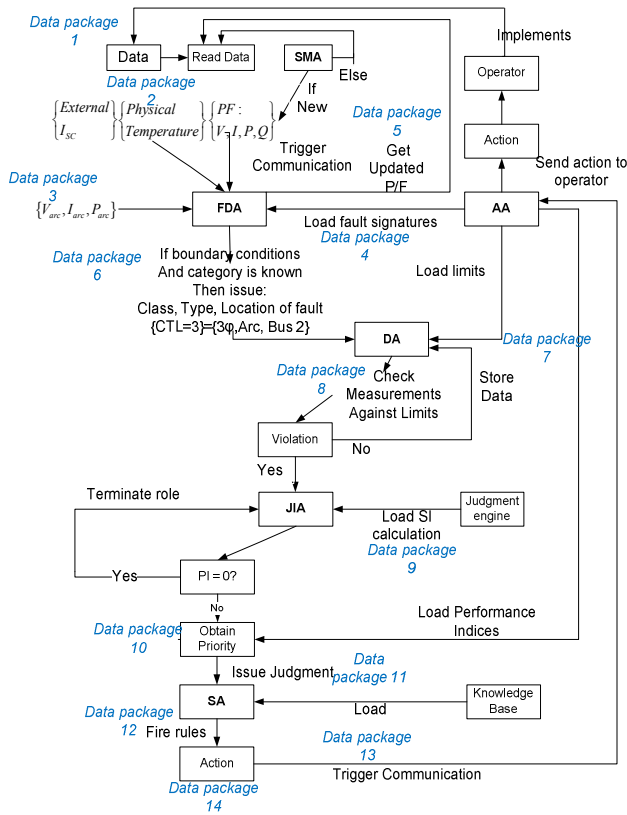


Fig.4. Agent Integration for Scenario 2

The results of the implementations of the agent integration scenarios of action scenarios are shown in Table 1. They demonstrate the functionality of the MAS architecture for the case studies run.

Table 2: Agent Integration Scenarios of Actions Scheduled

States, X_i and their parameters		Upper Limit	Base Case	Fault Case 1 at Bus 2	Shed Load Action for Fault Case 1 at Bus 2	Change Temp. Action for Fault Case 1 at Bus 2
M	BIL	75	59.27	61.051	59.3309	60.783
	T_g	135	50	150	150	100
	T_{XM}	100	40	150	150	150
	T_{CON}	100	40	90	90	90
E	I_g	2.5	1.1	3.0	3.0	3.0
	I_{XM}	2.4	0.9	2.6	2.6	2.6
	I_{CON}	2.2	0.9	1.2	1.2	1.2
	P_{arc}	250	0	1159.48	1176.040	1176.040
	CTL	-	0	3	3	3
	SI_{min}	-	0	0.6111	0.5418	0.5000
	SI_{max}	-	0	1.0706	0.7101	0.7071

Min_State	-	-	M	X	M
Max_State	-	-	E	E	E
Action	-	Do nothing	Shed Load	Adjust Temp	Isolate Bus

Violated cases are in bold

V. CONCLUSIONS AND DISCUSSIONS

In this paper, we design a complete MAS framework for fault detection in a format that can be further implemented easily in any platform selected. Future work involves the detailed programming of the MAS framework implemented on an agent platform. This would provide a more adequate management of the fault detection scheme since through a proper interface arcing can be simulated through hardware as well as software. This would allow for better comparison of the scheme with real time data.

The robustness of the scheme should be further tested by developing a higher level artificial intelligence such as Genetic Algorithms (GA) or Artificial Neural Networks (ANN). This would make the Scheduling Agent more proactive and able to be self learning because it will be trained via the ANN. These attributes will allow for the replacement of operators by the MAS as the system can respond without human input.

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VIII. BIOGRAPHIES

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