SHIPBOARD POWER SYSTEMS RECONFIGURATION: A COMPARED ANALYSIS OF STATE-OF-THE-ART APPROACHES

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SUMMARY

The Shipboard Power System (SPS) supplies power to navigation, communication, operation and critical systems. The capability of facing single or multiple faults is a mandatory issue for any vessel.
This paper reports a systematic comparison on SPS reconfiguration methods, where most recent contributions to the field have been classified according to taxonomy of criteria, such as: reconfiguration techniques, reconfiguration sub-problems, and characteristics of the electrical layer.
The reconfiguration procedure should be timely in restoring power in faulted areas of the ship, also to avoid subsequent cascade failures; the reconfiguration sub-problems involve priority definition among loads and operations, strongly depending from the electrical layers and the fault diagnosis methodology; moreover, reconfiguration techniques include several different control architectures and load priority schemas.
Literature results encompass several case studies, and employed methods have been deeply analysed.
Finally, some limits of the current state of the art have been identified.

1. INTRODUCTION

As technology evolves, shipboard electronic components demand high performance from the electric power system. The shipboard power system (SPS) supplies energy for communication, navigation, and operation systems. A robust SPS must be able to supply consistent power despite a variety of changing loads and network conditions. A power system consists of various components such as generators, cables, switchboards, loads, circuit breakers, bus transfer switches, and fuses.
The components are continuously updated even during navigation, and therefore power requirements and load demand may change. For instance, a power peak and/or a component failure may produce nearly instantaneous changes in load demand and system topology. In order to meet all of these changing situations, a shipboard system may employ various levels of reconfiguration of the electrical layer via computer-controlled switches across a variety of time scales. This problem of reconfiguration for power systems has been a topic of research for around three decades.
A few reviews studying the problem of the SPS reconfiguration may be found in literature. In [31] authors include a comparison between reconfiguration techniques applied to the terrestrial and SPS domain. They include an analysis of the SPS characteristics; studying and reviewing integrated protection, power distribution, and typical loads on-board. In another review [32] authors surveyed different formulations of the reconfiguration problem and the different techniques used in its solution. They compare the problem of SPS reconfiguration to that of large-scale systems, exploring the issue of optimal reconfiguration from a variety of perspectives. The authors highlight the reconfiguration research field has been mainly focused on finding an optimal switch configuration without considering the system dynamics that results from the switching actions and neglecting the transient behaviour resulting from the reconfiguration actions.
The purpose of this paper is to survey the existing literature in a reasoned manner for highlighting reconfiguration techniques according to intrinsic electrical and problem features.

2. MOTIVATION OF THE RESEARCH

The reconfiguration of an electric network in an SPS is a critical operation requested both to restore power supply, and to meet particular navigation requirements: it is possible, in fact, to change the network topology in order to isolate a fault, to transfer energy to vital loads in critical situations, or to optimize the electrical and electronic systems for the purpose of improving energy efficiency. At present, it is possible to implement several software reconfiguration methodologies.
Software systems are able to intelligently and effectively manage the electrical/electronic hardware on-board, thus allowing a sophisticated and real-time perception of the situation and a ready management of breakdowns, emergencies, energy peaks, etc. Various software methodologies are applicable also considering the underlying electrical architecture and the power supply type.
A typical problem that can be addressed with such reconfiguration methodologies is depicted in [5]. An SPS zonal architecture is composed of AC generators, switchboards, circuit breakers, loads and other electrical equipment, as shown in Figure 1.

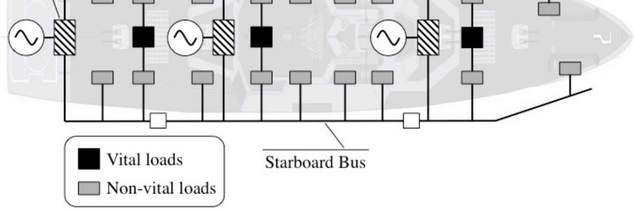

Figure 1: A typical zonal architecture of SPS from [9]

Loads are divided into vital and non-vital categories. Here, an approach using Multi-Agents System (MAS) is used.
The proposed paper studies reconfiguration issue with the aim to identify the relevant variables of the problem and highlighting possible correlations among them.

3. THE PROPOSED COMPARISON APPROACH

The needs motivating the proposed review have been identified by performing a domain analysis, a problem identification and, finally, the formalization of the resulting research questions.
After a fault is encountered, the reconfiguration of the SPS becomes a critical activity. It is desirable to restore power feeding in the shortest time in order to ensure system survivability. This depends on specific features of the system and the occurred problem. The current type and the electrical architecture are deemed to be significant for the reconfiguration strategy.
In the SPS, loads provide various services to the ship. According to the importance of the services being provided, loads in the SPS can be classified into non-vital, semi-vital, and vital, following an increasing priority order.
A common approach to the SPS reconfiguration is to supply power to high priority loads and to shed certain loads when needed.
The need for this systematic review is to understand the state-of-the-art about issues affecting SPS reconfiguration, specifically focusing on electrical features, reconfiguration algorithms, and reconfiguration sub-problems.
In particular, this paper considers a couple of research questions:

- RQ1. Is there a relationship between the electrical feature of the system and the technique used for the SPS reconfiguration?
- RQ2. How does the technique affect specific sub-problems of the SPS reconfiguration?

	Electrical Features		**Reconfiguration Sub-Problem**			**Reconfiguration Technique**	
Authors	**Current Type**	**Electrical Network Topology**	**Fault Scenarios**	**Priority Load Reconfiguration**	**Load Shedding**	**Algorithm/Method**	**Control Type**
Xue et al. **[1]**	AC	ZONAL	Single Failure	✓	✓	Particle Swarm Optimization	n/a
Momoh et al. **[2]**	n/a	ZONAL	Single Failure	✓	✓	Multi-Agents System	Decentralised
Solanki et al. **[3]**	AC	RADIAL	Single Failure	n/a	n/a	Multi-Agents System	Decentralised
Huang, Srivastava et al. **[4]**	AC	RING	n/a	n/a	n/a	Multi-Agents System	Decentralised
Belkacemi et al. **[5]**	DC	ZONAL	Single Failure	✓	✓	Multi-Agents System	Decentralised
Bose et al. **[6]**	AC + DC	ZONAL	Multiple Contemporary Failures	✓	✓	Non-Convex vs. Convex Approximation	Centralised
Ouyang et al. **[7]**	DC	ZONAL	Multiple Contemporary Failures	✓	n/a	Nonlinear Optimization	n/a
Ma et al. **[8]**	n/a	RADIAL	Multiple Contemporary Failures	✓	n/a	Differential Evolution	n/a
Butler-Purry **[10]**	AC	RADIAL	Single Failure + Faults Prediction	✓	✓	Multi-Agents System	Centralised
Shariatzadeh, Srivastava et al. **[11]**	AC	ZONAL	Single Failure + Multiple Contemporary Failures	✓	✓	Genetic Algorithm vs. Particle Swarm Optimization	Centralised
Padamati, Srivastava et al. **[12]**	DC	ZONAL	Single Failure + Multiple Contemporary Failures	✓	✓	Genetic Algorithm	n/a
Davey et al. **[14]**	n/a	MESHED GRID	Single Failure of Different Kind	✓	✓	Branch-and-bound optimization	n/a
Srivastava and Butler-Purry **[15]**	AC	RADIAL	Single Failure + Cascade Failures + Faults Prediction	✓	✓	Probability-based	n/a
Das et al. **[16]**	DC	ZONAL	Single Failure + Multiple Contemporary Failures	✓	n/a	Q-learning	Centralised
Pal et al. **[17]**	DC	ZONAL	Single Failure + Multiple Contemporary Failures	✓	n/a	Q-learning + Markov Decision Process	n/a
Bose et al. **[18]**	DC	ZONAL	n/a	✓	n/a	Delay Analysis Method	Centralised
Srivastava and Butler-Purry **[20]**	AC	RADIAL	Multiple Contemporary Failures	✓	✓	Rule-based Expert-system	n/a
Feliachi et al. **[21]**	DC	ZONAL	Single Failure	✓	n/a	Multi-Agents System	Decentralised

Table 1: Summary of data extracted by systematic review.

4. RESULTS

In this section, a detailed description of the compared papers is reported. In order to answer the two research questions, the most significant characteristics of each paper have been reported, dividing them according to the proposed comparison design, as it can be deducted from Table 1.
A large collection of papers has been selected from various journals and conference proceedings, from 2006 to 2016. After that, this collection has been filtered for identifying a highly focused sample. Title, abstract,

methodology section and conclusions of the surveyed papers have been analysed, as it is recommended in [27] and [28].
In the following, a detailed description of the electrical features, problem features, and reconfiguration characteristics of the surveyed papers is reported.

4.1 ELECTRICAL FEATURES

Electrical networks in vessels exhibit very different features. It is possible to classify them according to different classes; the most frequently discussed are: current type (AC/DC), and network topologies. In the following subsections, these will be further discussed.

4.1 (a) Current Type

As depicted in Table 1, several different shipboard power systems have been identified: 7 of them ([1], [3], [4], [10], [11], [15], [20]) refer to the adoption of AC current type, while other 7 ([5], [7], [12], [16-18], [21]) refers to DC current type; only in [6] a mixed AC-DC power system has been found. Both of them have advantages and disadvantages.
For instance, Alternate Current (AC) powered systems have smaller section cables, but bigger and heavier components, as told in [26]; moreover:

- AC generators should work using fixed speed, thus neglecting fuel consumptions efficiency,
- AC transformers are heavy and space-wasting,
- AC current quality is problematic, it is heavily affected by reactive power and harmonic issues,
- Military applications with a support for advanced electrical equipment and weapons are characterized by high-power pulsed loads and they can bring to severe damages to the system,
- AC systems are very diffused in terrestrial applications, also because of their ability to transport energy for long distances with a reduced loss of power. In a ship this may be an irrelevant factor because distances are relatively small.

Besides, Direct Current (DC) powered systems are composed of smaller components, that may save a lot of weight on-board. In particular [6], [16] and [18] refers to a particular kind of DC electrical network, called Voltage DC (MVDC), which specifics for power systems on ships design guidelines are discussed in [33]. Moreover they exhibit:

- compact power converters,
- easier connections,
- no reactive power and harmonic issues.

These features can bring to faults reduction and easier reconfiguration procedures. The main disadvantage of DC systems is that voltage shifts are more difficult to be realized than in AC systems where transformers do that with minimal losses.

4.1 (b) Electrical Network Topologies

The conducted survey highlights two main kinds of electrical network topologies: radial and zonal (see [29]).
In a radial topology, loads are often linked from a single connection point thus reducing ships' cabling. This topology doesn't seem to offer the possibility to segment the system into distinct zones, but it needs shorter cables. Radial topologies are used in 5 ([3], [8], [10], [15], [20]) of the surveyed papers.
The zonal electric distribution systems (ZEDs) seem to be the most used one, mainly for their reliability. In fact, the zonal architecture provides construction cost savings while it inherently offers more operational flexibility [9]. In ZEDs, two parallel and distinct bus rails run along the port and starboard sides of the ship. Components are then positioned across these buses, dividing power distribution in zones. It this way, the electrical network can be configured as a ring bus and it may also use a radial distribution methodology from the switchboards. Moreover, a single fault can be easily isolated and the reconfiguration procedure can be more effective. In [30] the zonal topology outperforms ring bus in terms of service interruption rates. Table 1 reports that 11 papers out of the 18 surveyed ones refer to zonal topologies ([1], [2], [5-7], [11], [12], [16-18], [21]).
Finally, two of the papers exhibit a ring topology or a meshed topology. The ring bus topology is a kind of network spreading around the ship and forming a single main power bus loop. In [4] authors use the ring topology in order to highlight a specific problem of redundant information accumulation (RIA), solving the problem transforming the ring topology into a radial one. A meshed grid has been found in [14]. This is a more complex topology that uses redundancy for power rerouting purposes.
All the discussed power topologies are feasible for shipboard power systems. However, there is always a trade-off between reliability and complexity. Complex topologies require more accurate reconfiguration strategies that have to be taken into account at design stage; instead, simpler topologies may be easily repaired, but they may also be subject to major breakdowns. The trade-off indeed mostly depends on the shipboard specific requirements.

4.2 RECONFIGURATION SUB-PROBLEMS

The reconfiguration sub-problems identified in the surveyed papers are: number of failures, priority-based load reconfiguration, and load shedding. They will be discussed in details in the following.

4.2 (a) Fault Scenarios

A reconfiguration strategy is necessary when a fault (or a series of faults), happens in an unknown instant. In particular, authors of [10] and [15] discuss the reconfiguration strategy that has to be adopted before an expected fault (for instance, before an attacker hits the targeted vessel). Other surveyed papers are related to reconfiguration strategies to be adopted after the occurrence of an unexpected fault.
In [1-3], [5] and [10], reconfiguration and self-healing procedures are related to the simplest case, that is the single fault. Once an anomaly has been detected, the first reconfiguration step is to identify the faulted zone. After

that, the reconfiguration approach may disconnect power to the faulted region, and/or it may try to repair that by using specific techniques.
Cases that need more sophisticated strategies occur when multiple faults are detected. In papers [6-8] and [20], the authors take into account the occurrence of multiple contemporary faults. In [15], authors both study the case of single and subsequent (cascade) faults.
Finally, in 4 of the surveyed papers ([11], [12], [16], and [17]), authors discuss both single faults and multiple contemporary faults.

4.2 (b) Priority Load Reconfiguration

An SPS includes several electrical equipments: cables, transformers, generators, loads, and many others. Obviously, not all the loads have the same importance for vessel survivability. For example, a military aircraft carrier can have sensible and vital loads such as weapon systems and operatory rooms. In the case of faults (i.e. due to an enemy attack) the most important electrical equipment in terms of survivability, like engines, countermeasure systems, and so on, should be restored as soon as possible.
The majority of surveyed papers take into account reconfiguration algorithms with priority-load aspects. In particular, authors of [11] and [12] use an objective function in order to maximize the power to unaffected loads and to redirect power towards high priority loads. In this sense vital and semi-vital loads are more relevant than non-vital ones. MAS-based methods ([2], [5], [21]) too, use priorities among agents.

4.2 (c) Load Shedding

In maritime applications, load-shedding policies may have the same importance (or even more) than in the terrestrial counterpart. Load shedding can be acted for different reasons: energy consumption reduction, power outages, and equipment protection. Most of the revised papers investigate load shedding-related problems.
For example, in [2] the proposed system shed the loads using a priority list. In [5] vital loads are non-sheddable loads that affect the survivability of the ship: the load-shedding scheme never intentionally interrupts power to vital loads; instead, non-vital loads are sheddable and they can be immediately disconnected without adversely affecting ship operations, survivability, or life.
In [11], a series of 8 different scenarios are shown, with the corresponding load shedding policies.

4.3 RECONFIGURATION TECHNIQUE

The reconfiguration techniques found in the surveyed papers are mainly based on different algorithms/methods and different logical control types. They will be further detailed in the following subsections.

4.3 (a) Algorithm/Method

Most recent approaches found in literature deal with the reconfiguration issue addressing it by using different methodologies. According to literature, the most used reconfiguration methodologies seem to belong to two main categories: Multi-Agent Systems (MAS), and others methodologies (mostly mathematical methods and knowledge-based methods).
Multi-Agent Systems: Mas-based methodologies are mostly used in shipboard reconfiguration, since each agent can be modelled as a proactive software entity that controls a single electrical component and communicates with other agents. An agent is an autonomous entity that has intelligence, reactivity, and adaptivity [22]. Basically, it is an information processor that executes actions based on communications among other agents and that actively reacts to surrounding environment. Multi-agent architectures are therefore highly taken into account when dealing with the reconfiguration issue. An agent can sense a fault, and besides repairing it, it can communicate to the other agents the new emergency situation. In this way, a global strategy that can reconfigure the electrical layer is possible distributing workloads and responsibilities among agents. Moreover, it is possible to use special hierarchical architectures that allow system users (i.e. senior officers) to control operations coordinating low-level agents, responding at run-time to sudden crises.
In surveyed papers, this approach is adopted by [2-5], [10], and [21].
The agents try to accomplish fault isolation and power restoration actions, determining which switch in the system needs to be closed and which needs to be opened, restoring the vital load rapidly, minimizing the number of switching operations. Reconfiguration behavior of agent systems performs during the period of reconfiguration requirement.
All the MAS-based approaches show similar characteristics, in particular:

- Decentralised control: the control logic in MAS is decentralised, avoiding problem such as single point of failures, and system topology dependency. This is possible often restricting communications from one agent to their neighbours. This kind of control achieves information awareness like centralised control, and broader functionalities such as decentralised control. This can be obtained using a communication network that should be as reliable as possible (i.e. see [2] and [4]).
- Priority-based load restore: as depicted in [2] and [5], the priority of loads is taken in account and agents restore power primarily to vital loads (engines, weapons), and after to loads of secondary importance; moreover, in [21] priority is taken into account also for energy management purposes.
- Heterogeneous architectures: agents can be applied in various kinds of electrical topologies, such as zonal ([2], [5], [21]), ring ([4]), and radial ([3]).

It is worth noting that MAS-based approaches deal only with single faults scenarios; dynamic behaviour where multiple contemporary faults happen is not present in literature contributions.
Agent-based prototypes are often realized using Matlab and Java Agent DEvelopment Framework (JADE) [13],

that is a software framework for the development of intelligent agents implemented in Java.

In this sense, a significant contribution of MAS-based reconfiguration can be found in [5]. The method achieves reconfiguration, restoration and load shedding goals, detecting and isolating faults, reconfiguring and restoring power to healthy loads and performing load shedding when necessary. The proposed system has been further implemented in microcontroller hardware and deployed on a power system test-bed for real-time testing and development purposes. The simulation and experimental results show that agents are capable of performing very fast reconfiguration and load shedding schemes.

Non-MAS methodologies: Among the non-MAS methodologies, the most used algorithms are based on mathematical and knowledge-based methods.

Mathematical methods are related to optimization and approximations algorithms.

In [1], authors use a discrete Particle Swarm Optimization (PSO) algorithm that achieves a rapid and optimal reconfiguration scheme for SPS. The method employs graph theory to generate an emergency reconfiguration, which can quickly restore the system with relaxed operation constraints; then, the particle swarm optimization (PSO) algorithm is used to improve this reconfiguration scheme while considering multiple objectives and stringent constraints. Authors also used a 32-bus electric shipboard test-bed that tests the performances. The model can execute a fast restoration that can satisfy the real-time application requirement, it can also consider multiple objectives for reconfiguration, including minimum power losses, the numbers of switching operations, the numbers of loops in the system and load shedding amount. The graph theory is applied for modifying the network topology in order to accelerate the solution.

In [6] authors consider a reconfiguration method based on low complexity Convex Approximation that is effective in finding optimal solutions. The cumulative distribution function (CDF) of the power delivered to loads is presented to showcase system robustness against random fault scenarios. The method finds an optimal reconfiguration trade-off between power delivery maximization and number of switching actions minimization. Moreover, a separate analysis observes the intermediate dynamic switch states while the reconfiguration is in progress to capture the trade-off more prominently.

The work in [7] presented a Mixed-Integer Nonlinear Programming optimization method to achieve the multiple objectives of reconfiguration, maximizing the restored load and minimizing the number of the switch operations. The DC-zonal SPS line and generator faults are considered, and the reconfiguration method is implemented by means of a software modelling system for mathematical optimization (GAMS) [19], which proves the correctness and feasibility of the proposed method.

In [8], authors use an improved Differential Evolution algorithm, combining chaotic initialization population, improving Pareto elitist selection strategy and adaptive mutation and crossover operator, that obtains an optimal solution. Obtained results are compared with other algorithms (NSGA-II [23], CADA [24], DEMO [25]), demonstrating a better efficiency than other algorithm in solving SPS reconfiguration.

It is possible to find methods that use knowledge in addition to intelligent and smart techniques.

In [11], an intelligent reconfiguration methodology, using a Genetic Algorithm (GA) and a Particle-Swarm Optimization algorithm (PSO), is used to find a post-fault optimal solution for the reconfiguration problem, to maintain the real power balance of the rest of the post-fault isolated system, and to reduce the effect of the fault with consideration of islanding (load shedding) process. The same authors in [12] apply the genetic algorithm for supply restoration and optimal load shedding.

In [14], the authors consider the dynamic impedance measurement as a key element in SPS monitoring. The way to analyse a dynamic shipboard power system is to use equivalent series and parallel impedances to represent power transmission and useful load power, respectively. The impedances are computed and updated in real-time using current and voltage measurements on a trunk line feeding. An optimization algorithm (binary branch and bound, for instance) is then applied determining the best configuration that meets critical power demand and minimizes losses.

In [15], authors present a predictive method for the reconfiguration of an SPS that utilizes electrical and geographical data and advanced techniques that determines the pre-hit reconfiguration actions for vital and non-vital loads, respectively. This probabilistic approach calculates the expected probability of damage (EPOD) for each electrical component on a ship. Further, a heuristic method uses the EPOD to determine control actions to reconfigure the ship’s electrical network to reduce the damage to the electrical system.

Authors of [16] and [17] propose a method for dynamic optimal reconfiguration. Optimal reconfiguration is viewed as a learning problem, rather than one of explicit optimization. Reinforcement learning is used as the learning approach. The specific algorithm used here is Q-learning, a very popular reinforcement-learning algorithm, based on dynamic programming. This off-policy method theoretically converges to the optimal reconfiguration. As Q-learning is an online approach, it can be deployed within a real SPS, where the algorithm can not only fine-tune itself with time but also re-adapt in the presence of non-stationary SPS environment. The proposed method also provides the correct sequence of switching operations that would lead to optimal reconfiguration in the shortest possible time.

Finally [18] studies a cross-layer end-to-end delay analysis method for real-time power system reconfiguration after the occurrence of faults. Several centralised sensor network topologies and their impacts on the delay distribution are analysed using a real-time analysis (RTA) framework. Real-time QoS guarantees with current and potential communication technology implementations (FDDI/Ethernet/Gigabit Ethernet) for shipboard are also compared. Specifically, cyber/physical system delays are modelled, including information aggregation, queuing, transmission, communication, and the computation associated with fault isolations and reconfiguration of switch status. One of the main metrics to quantify the performance of the cyber-physical system (CPS) is the real-time delay (a component of QoS). The proposed approach is based on probability theory, real-time queuing theory, and their application to CPS.

4.3 (b) Control Type

Another relevant aspect of the surveyed papers takes into account the control layer strategy. In large-scale shipboard grids, hierarchical control is a good choice because different layers can be controlled independently. Coordination methods are then related to communication techniques, mostly centralised and decentralised.

A centralised control for reconfiguration purposes can be obtained using a central controller, in a master/slave way. This way of control has the advantage that the control algorithm runs on a single node, but the difficulty increases with the increasing number of controlled components. Moreover, a failure on the main controller can lead to a global failure. This kind of control technique is used by authors of [6], [10], [16], and [18]. In particular, authors of [18] focus on communication delays in on-board sensor networks, comparing several centralised architectures: centralised network control (CNC); CNC with backbone; and centralised-cluster network control.

Decentralised control makes coordination independent from the main controller and can overcome single-points failures by distributing computational load among control objects. On the contrary, the accuracy of distributed measurements can impact the effectiveness of the SPS reconfiguration procedure. In [2-5] and [21] authors use the decentralised control technique.

Specifically, in [2] authors restrict agent communications to their immediate neighbours, making the system less dependent on the topology of the system and thus reducing the communication burden within the system. In [3] the locality of information makes the reconfiguration strategy topologically independent and it can works autonomously. In [4], authors deliberately highlights how reconfiguration procedures that require global information are centralised, and they overcome this drawback avoiding single points of failures with decentralised control.

Only in [10], authors implement the architecture of the self-healing system using a centralised monitoring and control framework, but using a multi-agent system with decentralised information and asynchronous computation.

Finally, in [11] authors use both centralised (GA) and decentralised (PSO) techniques.

5. DISCUSSION

In this section a reasoned discussion of the conducted survey is proposed.

5.1 ELECTRICAL FEATURES DISCUSSION

As mentioned before, electrical current types (DC and AC) have some advantage and disadvantage, especially when dealing with variables such as equipment weight, quality of current, and so on. Reconfiguration strategies don't seem to be affected by the existing on-board electrical current type. Moreover, electrical topologies are converging on zonal architectures, mostly because faults isolation and reconfiguration techniques may be more effective. Also, as can be depicted from Table 1, this kind of topology is always used by DC current-based on-board SPS. This answers to the first proposed research question (see 3.1 (b)).

5.2 RECONFIGURATION SUB-PROBLEMS DISCUSSION

As regarding reconfiguration sub-problems, number of failures management seems a key aspect. The most effective contributions in this sense are [10] and [15], that discuss faults prediction. Moreover, [15] takes into account both single fault and cascade failures. In addiction to this, all the MAS methodologies seem to take into account only single failures, lacking multiple-faults scenario.

Almost all of the surveyed papers take into account loads weighting and priority in reconfiguration schema. For instance, in [6] loads are explicitly weighted according to non-vital, semi-vital, and vital loads. Vital loads are restored in a manner such that those loads are serviced optimally and according to their priority. This means that vital and semi-vital loads are restored before non-vital loads. In [12] the used genetic algorithm considers loads multiplied by a weighting factor, so the vital and semi-vital load contributions are greater than the largest non-vital load contribution.

Load shedding aspects are mostly highlighted in [5], where vital loads are non-sheddable loads that affect the survivability of the ship or life. Power to these loads is not intentionally interrupted as part of a load-shedding scheme. The scheme is initiated when a generator can no longer supply all the electrical zones. In [15] the probability-based reconfiguration performs load shedding in a preventive manner, avoiding major damages and blackouts after a predicted fault.

In order to answer the second research question (see 3.1 (b)), it is possible to note that the number of failures management seems not correlated with a specific reconfiguration methodology, but they are addressed using approaches becoming from different categories. Also for load shedding and load priorities, reconfiguration strategy seems not correlated with a specific approach.

5.2 RECONFIGURATION TECHNIQUE DISCUSSION

It is worth nothing that most of the surveyed reconfiguration techniques are MAS-based. This is mostly for the granularity level obtained controlling electrical equipment through agents. In addition to that, all MAS methods provide decentralised control that is aware of single-point failures and does not request global information.

Only in [4] the authors consider the reconfiguration strategy from the information point of view, focusing on a specific problem of information inconsistency. They do not take into account the sub-problems of Section 3.

For non MAS-based methods, the most relevant reconfiguration techniques seem to be the Q-learning and PSO methodologies.

The Q-learning can be deployed within a real SPS because it is an online approach, where the algorithm cannot only fine-tune itself with time but also re-adapt in the presence of non-stationary SPS environment [16]. In [17] two Q-learning methods (∈-greedy and simulated annealing) are compared, where the learning curve of the former seems to reach faster the optimal reconfiguration solution.

It is worth mentioning, the PSO in [1] is able to establish an optimal reconfiguration scheme solving non-linear problem with multiple objectives, thanks to less computational complexity and computing time. In [11] the PSO is compared to a Genetic Algorithm (GA), where both simulation and real-time results indicate that GA is slower than PSO algorithm; nevertheless, it requires less number of tuneable parameters if compared to PSO.

Often the rate of convergence and the simplicity of calculations have been used as the only benchmarks of real-time implementability of reconfiguration algorithms. Safe implementations of a reconfiguration algorithm require the analysis of power systems dynamics during and after reconfiguration. The current body of literature lacks a rigorous examination of dynamic aspects of reconfiguration.

Surveyed papers lack of simulation data, so the repeatability of the experiment is quite difficult. Simulation data are only present in [3], [4], and [21]. Also, temporal aspects such as agents' reaction time, or the execution time of the reconfiguration procedure are neglected. Only authors of [5] report an estimation of the execution time of the algorithm of less than 20 ms., while authors of [21] report agent' steady state reaching after tens of seconds.

6. CONCLUSIONS AND FUTURE WORKS

In this paper, a comparative analysis of the state of the art approaches concerning smart and automatic reconfiguration on shipboard has been proposed. The review here proposed has taken into account three parameters:

- electrical features of reconfigured power systems,
- qualitative features of the problem domain,
- employed reconfiguration technique.

The SPS electrical features are related to the kind of used electrical current (direct or alternate), and electrical architecture topology (zonal, radial, ring, etc.).

Problem domain features embrace the reconfiguration approach adopted when facing failures. In particular, aspects like number of managed failures, priority load reconfiguration, and load shedding have been highlighted from surveyed reconfiguration techniques. Some papers take into account only single failures, while others consider multiple faults that can happen simultaneously, or subsequently, increasing the instability of the whole shipboard SPS. Once the fault has been identified, reconfiguration procedures can consider loads as equally important, or they can weigh them differently according to some priority schemas. Also the load-shedding procedure has been highlighted, because it can be important to protect some sensible load.

Another feature regards the control logic of the reconfiguration technique: a centralised control is less complex to implement and it is particularly effective, but it has the weakness that a problem with the single control component can compromise the managing of the entire SPS; a decentralised control overcomes this weakness, at the cost of an increased complexity in the design and implementation.

In conclusion, MAS-based approaches seem to be the most effective when dealing with single failures of heterogeneous kind; when multiple failures occur, best reconfiguration methodologies use soft-computing methods like Genetic algorithms, Differential Evolution algorithms and Particle Swarm Optimization. Also Q-Learning methods seems effective in this sense.

Future work will be related to a deeper exploration of MAS approaches, filling lacks of the management of multiple faults, and investigating communication issues among agents.

7. REFERENCES

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