A Self-Adaptation Exemplar: the Shipboard Power System Reconfiguration Problem

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In a vessel, the Shipboard Power System (SPS) is responsible for supplying energy to various services, such as navigation and communication. A research topic is the reconfiguration of the electrical scheme in case of either failure or damage. Indeed, after a fault, the software control system must ensure the ship's survival.

In a couple of earlier studies, we: (i) analyzed the relation between the electrical schema and the software control system and (ii) identified many common characteristics between the SPS problem and Self-Adaptive Systems domain. In particular, a systematic classification of the approaches for reconfiguration highlighted the need of environment monitors, decision-making procedures and a feedback loop among the others.

The purpose of this paper is to frame the SPS reconfiguration as a self-adaptive exemplar by highlighting scenarios, tasks, norms goals and quality aspects with the support of the IEEE specifications. The exemplar may serve for a twofold aim: (i) the SPS may be a new field to compare self-adaptive procedures, and, on the other side, novel self-adaptive approaches may improve the state-of-the-art in SPS reconfiguration.

Index Terms—**Shipboard power system, SPS reconfiguration, fault scenarios, self-adaptive systems, SAS exemplar.**

I. Introduction

Energy fault detection, isolation, and reconfiguration is an important and challenging problem in many disciplines such as grid management, aerospace engineering, automotive systems, and marine engineering.

In a vessel, the element that provides energy to navigation, communication, and operational systems is called Shipboard Power System (SPS). In several maritime scenarios, the electrical system can be damaged or affected by faults. A reliable SPS must be able to detect a fault, isolate it and, possibly, restore the power supply to other devices.

The design of modern, autonomous SPS requires the use of advanced optimization and control to ensure efficiency, vessel survivability, and security under different contingencies. Surveying the literature [1], we can distinguish an electrical layer and a software-based control system. The electrical layer consists of various electric and electronic equipment, such as generators, cables, switchboards, circuit breakers, fuses, buses, and many kinds of loads.

Software-based control systems have the responsibility to monitor and control the underlying electrical layer. In particular, the monitoring of faults is the ability to perceive voltage and current variations in electric equipment and to infer situations like short-circuits. After the identification of a fault, the control system has to enact a strategy for restoring energy to loads, called *SPS reconfiguration*. The reconfiguration involves changing the electrical scheme by acting on buses, circuit breakers, and switches, thus to interrupt and to isolate sections of the electrical layer, but maintaining other ones alive.

The problem of fast and efficient restoration of the SPS service has been a topic of research for around three decades.

In [2], authors compare reconfiguration techniques applied to the terrestrial and maritime domains. They include an analysis of the SPS characteristics, highlighting the need for an integrated protection and power distribution. In [3] authors make a survey on reconfiguration methodologies for flight control systems. The outcome is a classification of reconfiguration methodologies into two categories: multiple-model approaches, and adaptive control approaches. A similar finding emerged in [1], in which authors performed a survey of the most recent software-based SPS methodologies by comparing hardware and software properties. Deepening the similarity between SPS software layer and smart IT systems has been the objective of an earlier work [4] in which SPS reconfiguration problem has been explicitly compared to the state of the art in self-adaptive systems.

This work aims at framing the SPS reconfiguration problem as a self-adaptive exemplar by resuming the experience of [1], [4] and exploiting the IEEE recommendations and guidelines for effective maintenance of medium-voltage direct current (MVDC) electrical power systems [5], [6].

The objective is twofold. Firstly, the self-adaptive community requires to populate a repository of examples, challenge problems, and solutions that can be used to motivate research, exhibit solutions, techniques, and compare results [1]. Moreover, we retain that novel self-adaptive approaches may improve SPS reconfiguration and provide new stimulus for the state-of-the-art.

This paper is organized as follows: Section II describes the Shipboard Power System; Section III deals with the SPS reconfiguration problem specifying possible fault scenarios; Section IV describes the reconfiguration from a standpoint of self-adaptive problems, specifying in Section V the reconfiguration standards and procedures; in Section VI a brief overview on recommended analysis; finally, in Section VII some conclusions and discussions.

[1]A set of exemplars are available at https://www.hpi.uni-potsdam.de/giese/public/selfadapt/exemplars/

II. The Shipboard Power System

A typical Shipboard Power System (SPS) [6] is composed of a series of sub-systems specifically conceived for managing power, navigation, cargo, weapons, and other operative functions, that embraces a series of electric and electronic equipment.

The electric components can be classified in main and auxiliary power generators, buses, propulsion motors, energy storage components, and ship loads. They can use either AC or DC currents, so often a series of AC/DC and DC/DC converters are on-board. In the last few years, the DC-based equipment is the most used because of smaller components, less weight, and fewer synchronization problems. Therefore, frequently, the shipboard power systems are medium-voltage direct current (MV-DC) SPS. A typical example of an electrical scheme is depicted in Figure 1.

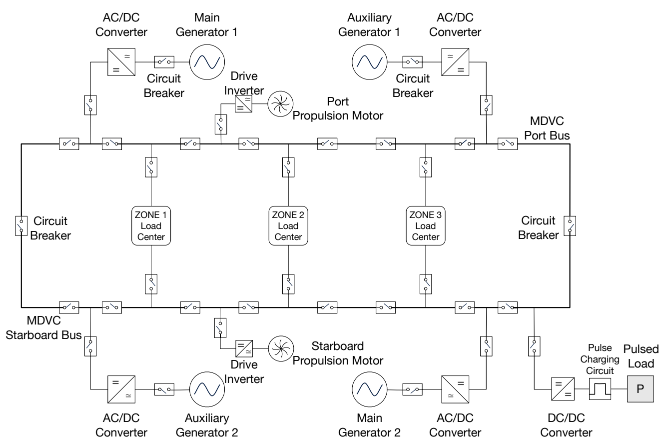

Figure 1: A typical SPS topology.

The onboard electrical equipment can be arranged using ring or radial distribution, that perhaps are difficult to manage in case of faults because of the dependency of the components from the electric distribution system. Recently, the SPS is architecturally divided into zones (as shown in Figure 1), where each of these zones can be easily connected/disconnected, modifying at run-time the power flow, by changing the electrical layer topology.

The control of these functionalities is delegated to the control system, that perceives all the electric equipment and it is able to detect failures, such as short-circuits, damages, faults and so on. After the detection of a fault, the control system may enact strategies for repairing the SPS, using an action called *reconfiguration*.

III. The SPS Reconfiguration Problem

In critical scenarios (i.e. a battle), but also during normal navigation, the ship can be damaged and affected by faults and failures. The control and protection functionality is often implemented at design-time using a ship-wide power and energy management control system, that can protect the SPS from faults by interrupting and isolating sections of the electrical layer using protection components and reconfiguration algorithms.

Reconfiguration algorithms are delegated to overcome the failures, in best possible way, according to a series of goals, scenarios, and decisions based on functional and non-functional requirements. Reconfiguration actions are also prioritized according to loads classification: vital and primary loads are non-sheddable loads that directly affect the ship survivability, while secondary loads (non-vital loads) can be disconnected for power routing purposes.

From a recent work [1] it is possible to depict that most of the reconfiguration techniques in literature are software-based and enact strategies basing sophisticated real-time perception and configuration management. The surveyed and classified reconfiguration algorithms span from mathematical optimization to evolutionary approaches and multi-agents system methodologies.

The reconfiguration is also affected by scalability issues, because of the number of controlled equipment, the complexity of electric architectures, the presence of single or multiple failures, and the need to apply loads priorities and load shedding. Moreover, it heavily depends on the designed electrical architecture.

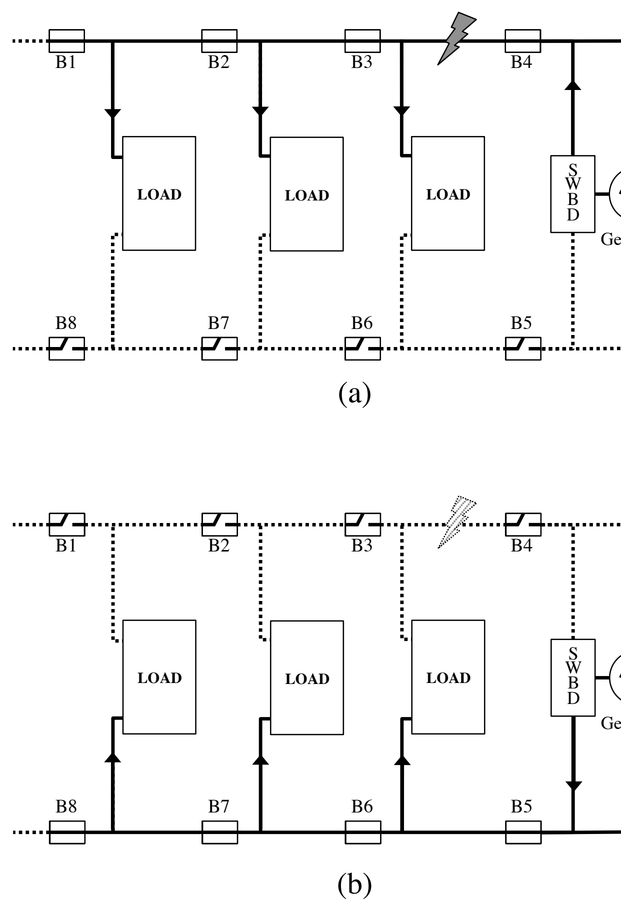

Figure 2: A fault on a bus of the SPS (a); the re-routing of power flow acted by the reconfiguration algorithm that isolates the fault (b).

We illustrate a simple reconfiguration action necessary in the case of fault detection. The example takes into account a few components, but clearly, the scalability of the problem may be of higher order in big vessels such as cruise ship or aircraft carrier.

As depicted in Figure 2, the starboard bus brings power to loads. In this particular case let us consider closed breakers B1, B2, B3 and B4, and opened those breakers belonging to the starboard bus (from B5 to B8). In this way, all the three zones bring power from the port bus using the AC Generator. Suddenly a major fault on the feeder between B3 and B4 breakers happens (Figure 2-a). For isolating the fault, it is necessary to open these breakers. After the opening, the power will not flow along the port bus, and all the three zones are in black-out situation. The control system detects the fault and acts a reconfiguration procedure that must repair the black-out. The power can flow to loads from both buses using zonal distribution. The reconfiguration involves closing the breaker B5, B6, B7, and B8 to feed loads using the starboard bus (Figure 2-b).

A fault, like the one described above, may be managed using smart and proactive reconfiguration methodologies, that at run-time have to detect, isolate, and restore the system (or part of it). The reconfiguration strategy will attempt to recover the fault after a precise series of steps, that can be set at design-time, or decided at run-time.

In the next section, the proposed comparison approach will discuss these reconfiguration procedures from a self-adaptation point of view.

IV. SPS RECONFIGURATION AS A PROBLEM OF SELF-ADAPTATION

The SPS reconfiguration can be achieved with several techniques, having their roots in research fields like artificial intelligence, operations research, and knowledge engineering. As said before, previous studies highlight that SPS has several features in common with self-adaptive systems.

The first relevant property concerns the monitoring of the electric layer, in order to identify network features and eventually to detect faults.

The second –even more interesting– feature is the implementation of various types of feedback loops [7].

The SPS control system and self-adaptive systems come from different domains and a direct association has never been done and for this, the terminology is sometimes confusing to conciliate. However, despite a different vocabulary, probably SPS and self-adaptation share more than what is immediately visible.

In our previous papers, a systematic state-of-the-art review was carried out about the reconfiguration of shipboard power systems [1]. From this study, it emerged that software-based SPS reconfiguration strategies have characteristics similar to self-adaptive systems. Therefore, a comparison has been made between these two research areas to provide empirical evidence of a possible synergy [4].

The baseline for self-adaptive systems is constituted by two research agenda ([8], [9]), some position papers about relevant features of self-adaptive systems ([7], [10], [11]) and a couple of papers proposing a taxonomy of types of adaptation [12], [13].

Studying the relation between SPS and self-adaptation, three qualitative variables have been identified:

- algorithms used for the reconfiguration;
- reconfiguration sub-problems: loads priority, loads shedding and the number of failures that the system can handle;
- self-adaptive characteristics: goals/quality aspects, reconfiguration algorithm, decision-making process, and feedback loop architecture.

It emerged the following features are relevant for implementing a self-adaptive shipboard power system:

- specification of goals and quality assets
- run-time decision-making
- anticipation of changes
- techniques for reaction
- feedback loop
- human in the loop
- duration of the adaptation

The specification of goals and quality assets indicates the flexibility of the system to deal with high-level and dynamic requirements [8].

The degree of autonomy in the decision process measures the ability of the system to take decisions about its behavior: the level of abstraction used in the decision process has a great impact on the mechanisms for the adaptation [9].

Assuring the continuity of service is often related to the ability to anticipate failures and changes [8].

The techniques for reaction capture how the system deals with unanticipated changes.

The feedback loop is a fundamental part of the architecture of a self-adaptive system, and many reference models are available in the literature [8], [7], often including the human in taking some role in it.

Finally, the time aspect is central to a self-adaptive system, because it actively contributes to reliability and robustness [8], [9].

From this analysis, it was evident the SPS reconfiguration problem is a good candidate as self-adaptive system exemplar. In order to enforce this claim, we used run-time decision-making process for classifying the type of SPS adaptation [12], [13]. During the analysis, we used the guidelines depicted in Table I.

Table I: Run-Time decision making activities and decisions

Adaptation	Monitoring	Execution
Type I	environment	reconfiguration strategy
Type II	quality aspects	strategy selection
Type III	goal satisfaction	ad-hoc assembled strategy
Type IV	self-inspection	evolution

The result is that, so far, only three types of adaptive SPS exist in the literature (at best of our knowledge).

Type I. This kind of system is able of monitoring the electrical scheme to enact the strategy. However, the decision-making is a hard-coded strategy (like *if..then..else* statements or a set of rules).

Type II. The system is instrumented with more alternative strategies to adopt, and the strategy is selected at run-time.

This kind of system is also able of measuring non-functional aspects that allow taking a decision about the optimal strategy to be used.

Type III. The system is able of assembling new strategies according to the contextual needs. This kind of system is able of evaluating the degree of satisfaction of the goals to be addressed. Moreover, it is able to evaluate possible deviations and to decide, at run-time, to assembly ad-hoc functionalities.

The next section will discuss IEEE standards and common procedures that are suggested for the design phase of the SPS power system, where the capabilities of each component are used for a global goal satisfaction. Common aspects such as QoS have been found in both SPS reconfiguration and SAS systems.

V. SPS reconfiguration: standards and procedures

The IEEE industry applications society issues some recommended practice documents. In particular, we refer to the IEEE 1709-2010 "Recommended Practice for 1 to 35 kV Medium Voltage DC Power Systems on Ships" [6] and the IEEE "Recommended Practice for Electrical Installations on Shipboard" [5].

These standards specify electrical engineering methods and practices for implementing power distribution and delivery systems for Medium Voltage DC (MVDC) on-board power systems. The purpose is to provide guidelines for a proper analysis of parameters that characterise MVDC survivability and continuity of power supply, always maximising on-board safety. These documents describe the impact of MVDC on all electrical components and suggest appropriate requirements for the implementation of MVDC power supply system thus to generate, accumulate and distribute the adequate power to loads.

Firstly, the specifications identified some higher-level goals:

- Ship-wide power and energy management control: the centralised or distributed ship-wide power management control communicates with all energy sources and vital loads to prioritise and optimise the power flows throughout the ship. This power controller maximises the continuity-of-service of vital loads during reconfiguration operations;
- System Protection: some MVDC components, such as alternating current generators, can be protected against damage caused by faults using automatic circuit breakers. DC system protection is obtained through a combination of converter control and other DC circuit breaker devices;
- Efficiency: the electrical efficiency of the system depends on the mission of the ship and service conditions. It is critical to achieving high efficiency under a range of possibles scenarios. The efficiency calculations of the MVDC system should include generators, motors, converters, storage devices, transformers, cables, and so forth.

In particular, power management must meet the following sub-goals:

- Manage power under normal conditions;
- Maintain QoS;
- Maximise survivability.

The control system, based on real-time monitoring of generators and loads, should survey of critical conditions and propose actions to avoid instability and system collapse. The design of the control system should incorporate human factor engineering to enable operators to maintain situational awareness and take appropriate measures during normal and emergency conditions.

The standards describe a typical functional scheme of an MVDC consisting of several functional blocks (Figure 3). The fundamental components include:

- Main power generation: the component that transforms the power of the gas turbine into electrical energy;
- Energy storage: a stand-alone power source that provides power to the system, if necessary;
- AC/DC load: loads that compose the ship services;
- MVDC bus: a functional block that allows feeding, interrupt and isolate MVDC components.

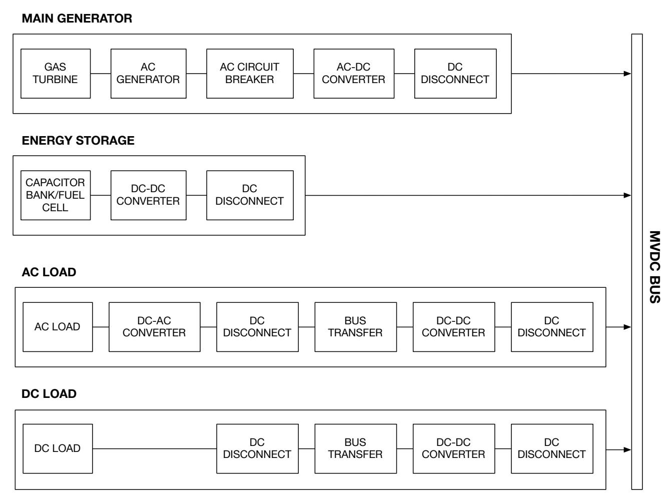

Figure 3: The main components of the SPS MVDC connected to the bus, and their subcomponents.

The IEEE standard also provides an overview of capability, goals and quality aspects of SPS components.

The main operations of the functional blocks are connection/disconnection, configuration, and isolation. Each functional block of Figure 3 can meet one or more of these functions, as depicted in Figure 4. These operations are intended as component capabilities because autonomy is fundamental to allow each block to act independently from the rest of the system. For instance:

- A circuit breaker can interrupt, isolate and configure a load;
- A fuse can break and isolate, but it cannot configure (a fuse can not turn on and therefore can not be configured);
- A load switch can isolate and configure;
- The power electronics on the output of the generator can only interrupt.

Moreover, according to specifications [5], each functional block has some goals to meet. Table illustrates some of these MVDC component goals:

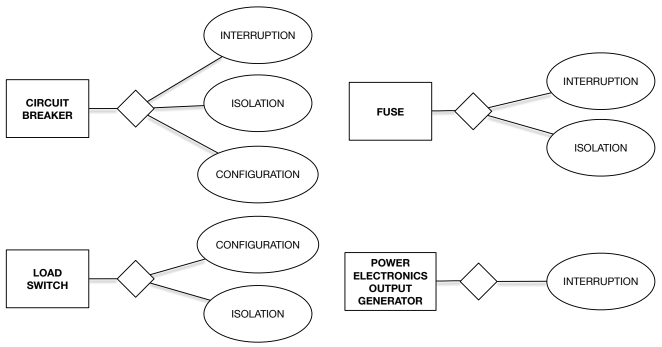

Figure 4: SPS MVDC sub-components and their respective capabilities.

Table II: The MVDC components and their respective goals.

MVDC Component	Goal
Main generator	to generate power
Energy storage	to store and stabilize energy
Ship service	to feed the loads

Quality aspects describe non-functional constraints and QoS metrics that an SPS must satisfy. An example of a QoS metric is the mean-time-between-service-interruption (MTBSI) that norm transients during normal system operation (it is not taken into account during exceptional events like battle damage, collisions, fires, or flooding).

Therefore, loads can be categorised into four QoS categories, as depicted in Table III that adopts two system-dependent time thresholds (*t1* and *t2*) related to the interruption of the loads.

Table III: Loads classification.

Classification	Description
Un-interruptible	Service interruption time $t \leq t1$
Short-term interrupt	Service interruption time $t1 \leq t \leq t2$
Long-term interrupt	Service interruption time $t \geq t2$
Exempt	Loads do not need to be restored within time t2

Reconfiguration time *t1* is defined as the maximum time to reconfigure the distribution system without causing additional damage. For a system employing conventional circuit breakers, *t1* is on the order of two seconds.

Generator start time *t2* is defined as the maximum time to bring the slowest power generation module on-line. Generator start time is typically on the order of one to five minutes.

Quality studies should assess whether the MVDC system is suitably designed to meet QoS requirements, such as the following:

- load shedding strategies;
- rapid-response, energy storage;
- propulsion motor regenerative power;
- an optimal integration of these power management approaches into a load-centric system response;
- the reliability measures associated with the selected approaches;
- the survivability measures associated with the selected approaches.

Under the conditions in which the power system cannot serve all loads, due to damage or equipment failure, power management is required to implement a survivability response and accomplish system functional and performance requirements. In general, the survivability response is shedding the appropriate loads in the order of their priority.

At the design stage, the system designer should capture all the relevant system conditions (e.g., steady state, fault, dark-ship-start, black-start, etc.) with the appropriate tools and/or methods. Also, it should obtain the necessary information to fully characterise and assess system performance in order to verify and refine the design.

In this, simulations and modelling of the system play an essential role. In literature, there are guidelines that define the methodology to be used in the development of the software and the standards that must be applied. Just to report an example, the IEEE guidelines [5] recommend distributed and hierarchical systems (MAS) for modelling SPS reconfiguration operations.

VI. Analysis of SPS Reconfiguration

The IEEE recommendations [6], [5] provide guidelines to assess the Quality of Service (as discussed in the previous section).

In practice, it could be important to use a MVDC power system simulation that takes into account small and large ‘perturbations’. This goes through considering all the possible fault types and their combinations:

- short-circuit between 2-3 bus lines;
- short-circuit between bus line and ground;
- equipment short-circuit;
- control system fault (communications, sensors etc.).

Guidelines highlight that fault management should ensure post-fault reconfiguration actions in combination with stability studies (to verify stable recovery), also granting system transients during the reconfiguration. The recommendation suggests a computer system analysis that *"shall contain enough detail to properly represent the transient behaviour of all the components governing the respective event"*.

From our perspective, self-adaptive methodologies are very suitable to address this need. It can add the *quid-pluris* that is missing in current state-of-art on management and control systems based on stimulus-response approaches.

Indeed, [5] describes the Electrical Power System Concept of Operations (EPS-CONOPS), that is a statement of the required behaviours of the electrical SPS based on the expected use of the ship. The relevant part of operating conditions requirements and transitions and the possible approaches is schematized in a conceptual mapping shown in Figure 5.

In particular, it distinguishes between nominal operations and restorative operations during the occurrence of failures and damage scenario.

Nominal operations focus on mission conditions and to possible approaches that regulate electrical load analysis in light

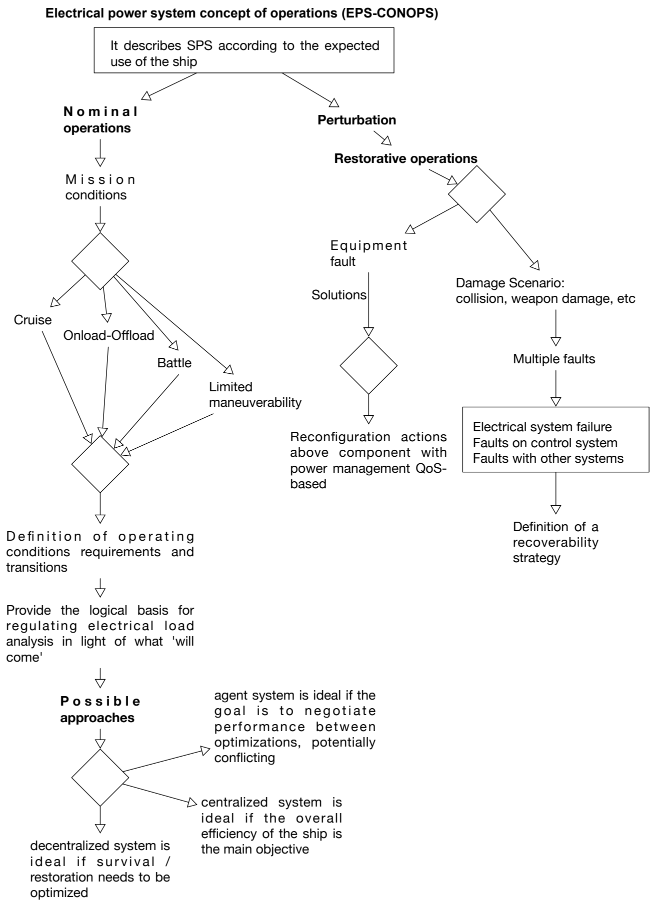

Figure 5: Conceptual map of the EPS-CONOPS operating conditions requirements and transitions.

of what 'will come'. Apart the considerations about decentralised and centralised control systems, they suggest explicitly the use of agent-based systems for negotiating performance between many components with the aim of optimisation.

Restorative operations occur in the case of perturbations and they focus on returning the SPS power system to a nominal condition, taking into account single faults and reconfiguration actions, and multiple damage scenario where a recoverability strategy must be defined.

VII. Conclusion

The conducted analysis has highlighted the correlation between SPS control systems and self-adaptive systems. We believe the SPS reconfiguration is suitable to be taken as a self-adaptive exemplar, especially if we consider goals, quality aspects, monitoring of the entire system, and other self-adaptive attributes.

As suggested by some IEEE guidelines, the implementation of a decentralised control system can be winning if adopting a multi-agents system strategy. In this perspective, our future works will aim at using agents in conjunction with self-adaptive abilities for implementing the control logic of an SPS.

We retain this a successful marriage in which innovative self-adaptive approaches may improve SPS reconfiguration techniques and, besides, the resulting framework could be used for comparing different approaches to self-adaptation.

References

[1] L. Agnello, M. Cossentino, G. De Simone, and L. Sabatucci, "Shipboard power systems reconfiguration: a compared analysis of state-of-the-art approaches," in *Smart Ships Technology 2017, Royal Institution of Naval Architects (RINA)*, pp. 1–9, 2017.

[2] W. M. Dahalan and H. Mokhlis, "Techniques of network reconfiguration for service restoration in shipboard power system: A review," *Australian Journal of Basic Applied Science*, vol. 4, no. 11, p. 55565563, 2010.

[3] I. Hwang, S. Kim, Y. Kim, and C. E. Seah, "A survey of fault detection, isolation, and reconfiguration methods," *IEEE Transactions on Control Systems Technology*, vol. 18, pp. 636–653, May 2010.

[4] L. Agnello, M. Cossentino, G. De Simone, and L. Sabatucci, "Is shipboard power reconfiguration a self-adaptive problem? a systematic literature review," Technical report, CNR Institute, RT-ICAR-PA-17-01, 2017.

[5] "Ieee recommended practice for shipboard electrical installations – systems engineering," *IEEE Std 45.3-2015*, pp. 1–74, July 2015.

[6] "Ieee recommended practice for 1 kv to 35 kv medium-voltage dc power systems on ships," *IEEE Std 1709-2010*, pp. 1–54, Nov 2010.

[7] Y. Brun, G. D. M. Serugendo, C. Gacek, H. Giese, H. Kienle, M. Litoiu, H. Müller, M. Pezzè, and M. Shaw, "Engineering self-adaptive systems through feedback loops," in *Software engineering for self-adaptive systems*, pp. 48–70, Springer, 2009.

[8] B. Cheng, R. de Lemos, H. Giese, P. Inverardi, J. Magee, J. Andersson, B. Becker, N. Bencomo, Y. Brun, B. Cukic, *et al.*, "Software engineering for self-adaptive systems: A research roadmap," *Software Engineering for Self-Adaptive Systems*, vol. 5525, pp. 1–26, 2009.

[9] R. De Lemos, H. Giese, H. A. Müller, M. Shaw, J. Andersson, M. Litoiu, B. Schmerl, G. Tamura, N. M. Villegas, T. Vogel, *et al.*, "Software engineering for self-adaptive systems: A second research roadmap," in *Software Engineering for Self-Adaptive Systems II*, pp. 1–32, Springer, 2013.

[10] M. Salehie and L. Tahvildari, "Self-adaptive software: Landscape and research challenges," *ACM Transactions on Autonomous and Adaptive Systems (TAAS)*, vol. 4, no. 2, p. 14, 2009.

[11] N. A. Qureshi, I. J. Jureta, and A. Perini, "Requirements engineering for self-adaptive systems: Core ontology and problem statement," in *International Conference on Advanced Information Systems Engineering*, pp. 33–47, Springer, 2011.

[12] D. M. Berry, B. H. Cheng, and J. Zhang, "The four levels of requirements engineering for and in dynamic adaptive systems," in *11th International Workshop on Requirements Engineering Foundation for Software Quality (REFSQ)*, p. 5, 2005.

[13] L. Sabatucci, V. Seidita, and M. Cossentino, "The four types of self-adaptive systems: a metamodel," in *Smart Innovation, Systems and Technologies, Proceedings of the 10th International KES Conference, Algarve, Portugal, 21-23 June*, vol. 76, 2017.