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Review of Network Topologies and Protection Principles in Marine and Offshore Applications

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Abstract—An electric fault that is not cleared is harmful in land applications, but in marine and offshore sector it can have catastrophic consequences. If the protection system fails to operate properly, the following situation may occur: blackouts, fire, loss of propulsion, delays in transportation, collision with the cliff, reef or other ships and electrical shocks to humans. In order to cope with the unwanted effects of a fault, several protection strategies are applied, but complexity of the marine and offshore applications is continuously increasing, so protection needs to overcome more and more challenges. As result, development of new protection techniques that can offer improved functionalities compared to the actual solutions for marine and offshore applications is needed. This paper reviews the network topologies in such applications and presents the requirements of a system able to protect them. Also, a brief overview of the protection principles for a generic power system is presented.

Index Terms—Electric fault, grounding, marine and offshore sector, network topology, protection, protective relay.

I. INTRODUCTION

Electrical engineering uses 2 types of materials: conductors and insulators. As result, there are 2 basic types of faults that occur in the electric circuits:

- *short-circuit fault*, defined as the accidental electrical contact between 2 elements of the circuit following an insulation breakdown or caused by external interventions and further classified in *phase* and *ground* faults [1]
- *open-circuit fault*, defined as the accidental interruption of the electrical path between 2 elements of the circuit following a conductor damage or caused by external factors

This paper approaches the 3-phase AC power systems and the electrical faults appearing in these systems are discussed and presented in Fig. 1. Apart from these, other abnormal conditions can occur, as: inter-turn faults in electrical machines, overloading of equipment, active power deficit, under-excitation of the synchronous generators, over-fluxing of transformers, loss of synchronism or mechanical defects (oil leakage, tap-changer breaks, jammed switchgear) [1].

Protection system needs to minimize the negative effect of the faults and it is defined as the technology that isolates the affected component from the rest of the grid during the faulty or abnormal conditions [2]. This definition is also valid in marine and offshore applications, where the term *marine* refers to the vessels, while the term *offshore* refers to the oil and gas

sector. Both marine and offshore applications are addressed onwards with a more generic name: maritime applications.

Maritime applications are islanded power systems [3] and their protection system is challenged by the specific issues of the maritime sector [4]. Every maritime application needs to fulfill the requirements of one classification society: Lloyd's Register, Bureau Veritas, Det Norske Veritas & Germanischer Lloyd, American Bureau of Shipping or other. Similarly, a maritime protection system needs to comply with the requirements of the associated class.

The specific challenges of the maritime sector are presented in section II, as they represent the prerequisite requirements for protection. Moreover, as the protection strategies applied in a maritime power system are dependent on the electrical fault and the fault itself is dependent on the network, this paper also studies the power network topologies. Section III presents a review of the power system grounding methods and the possible network topologies of a maritime application. Power system protection is approached in section IV. Section V concludes this paper and presents the main directions of research to be followed in the future.

II. SPECIFIC CHALLENGES IN MARITIME SECTOR

Among the main issues that characterize the power system of a maritime application can be mentioned:

- low short-circuit power and current – affects the forward relay settings of protection system, shown in Fig. 2 [5]
- variable generation and load profiles – affects the backward relay settings of protection system, shown in Fig 2 [5]
- reconfiguration of the network changes the short-circuit current seen by the protective relays [5]

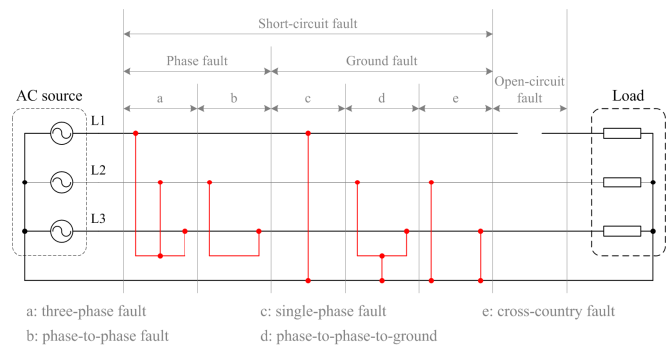


Fig. 1. Basic electrical faults in a 3-phase power system

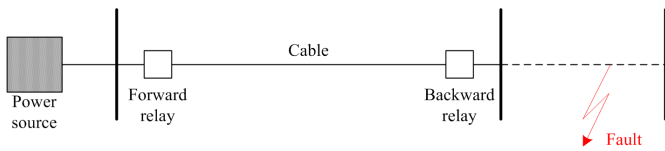


Fig. 2. Single-line diagram of a faulted power system

In top of these issues, the “survivability” principle is very important in maritime applications and it is defined as the continuous operation of the essential devices regardless of the system conditions [6]. Fig. 3 illustrates 2 different approaches regarding continuity of operation of the healthy section of the power system during the fault [7]:

- continuity of service – during the fault, the healthy circuits are disconnected and after clearance of the fault, the supply of the healthy circuits is reestablished (CB3 is always closed and CB1 recloses after the fault)
- continuity of supply – during and after a fault, the supply of the healthy circuits is permanently ensured (CB1 and CB3 are always closed)

In order to achieve the survivability condition of the power network, the protection system needs to clear the fault and to ensure continuous operation of the essential loads. The following techniques are applied:

- zonal ship/platform design, which means that the network is divided in several zones in such way that operation of electrical equipment is not affected by malfunctions appearing in a different zone [6]
- utilization of several distributed generators (e. g. diesel or gas-turbine driven) [8], connected to minimum 2 bus bars
- flexible architecture of the network, using various CBs (Circuit Breakers) or tie-breakers, so in faulty conditions the power is transmitted using alternative paths [9]

New maritime applications introduce higher generation and load levels, power electronics based consumers [9] [10], more complex networks and higher voltage levels [11]. Moreover, operation of the protective relays may be disturbed by the high

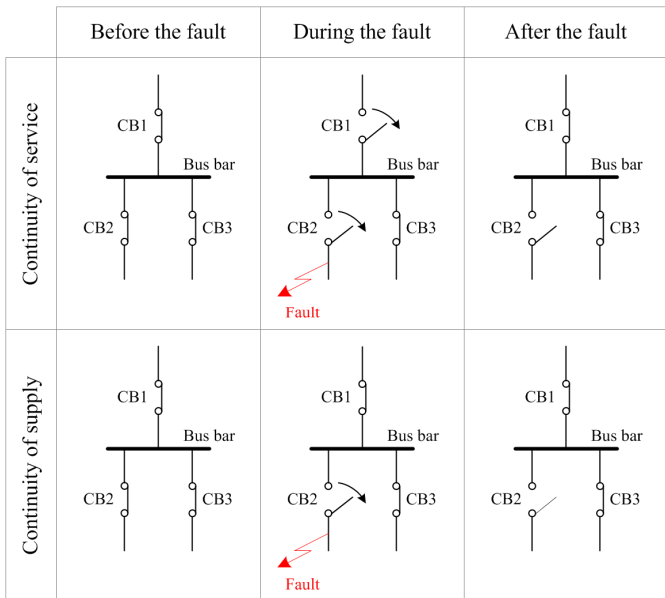


Fig. 3. Continuity of service/supply [7]

start-up currents of motors [3] or by the harmonic generation of the power electronics based devices [9]. All these challenges need to be addressed by the power system protection of the maritime applications.

III. NETWORK TOPOLOGIES IN MARITIME APPLICATIONS

A. Power system grounding

The grounding method influence the electrical faults in a power system. The vector group of the power transformers influence propagation of the fault [12], overall reliability of the power system [13] and the harmonics level. As result, there is a strong relation between the power system protection and the grounding method of an electric network. Fig. 4 presents the main approaches for power system grounding in the MV maritime sector [8] [13].

The maritime applications can have Low Voltage (LV) power systems (rated voltage below 1 kV) or Medium Voltage (MV) power systems (rated voltage above 1 kV) [8] [14]. Most of the faults originate in a single-phase fault [15], thus most of the LV power systems are ungrounded [16]. The resistive grounding is typically found in the MV power systems [14] and it is achieved using a low or high resistance that limits the ground current during a fault.

Although the ungrounded power systems are not connected intentionally to the ground, a capacitive coupling between the phase conductors and ground exists [7] [17]. The ungrounded power system allows continuity of supply to the healthy phases with the single-phase fault [18] and is relatively safe for the personnel with a ground fault [13], as the fault current is typically low (around 1 A). However, this method of grounding is characterized by high overvoltage transients and the exact fault location is not possible [13].

The high resistance grounding allows continuity of supply to the healthy phases with a single-phase fault, it is a relatively safe method of grounding for the personnel during a ground fault and permits fault location [13]. Grounding through a low resistance permits fault location, but is not allowing continuous operation of the healthy phases with the single-phase fault [13].

Other solutions for grounding of the power systems is represented by the grounding transformers, used in some MV maritime applications. Fig. 5 presents briefly the distribution transformer, used when the AC source neutral is available and the wye-broken delta and zig-zag transformers, typically used when the neutral of the AC source is not available [17].

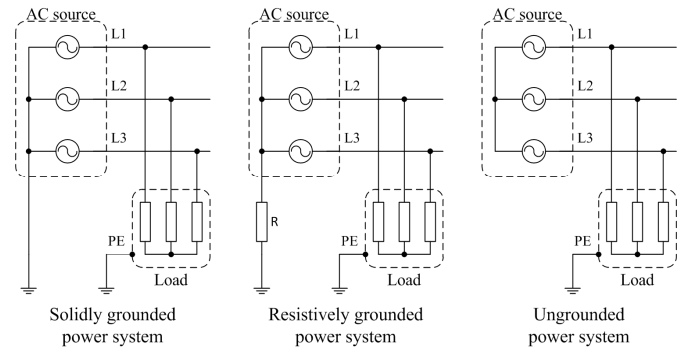


Fig. 4. Power system grounding (3-phase 3-wire MV system)

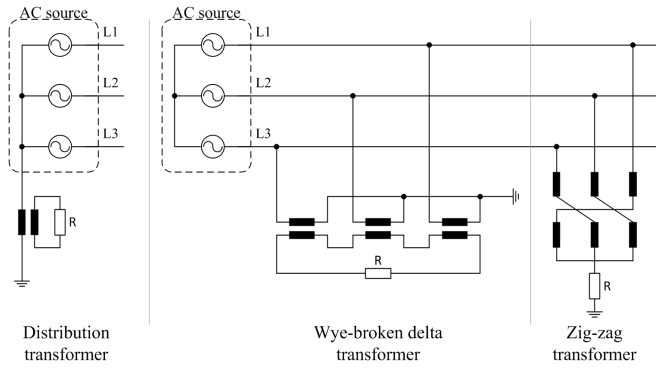


Fig. 5. Grounding transformers [17]

B. Network topologies

Total installed power in maritime applications range from a few MW to hundreds of MW. The complexity of the maritime distribution network varies according to the tonnage and total installed power. This sub-section presents 2 network topologies for the marine sector and 2 network topologies for the offshore sector. The purpose is to present some basic methods to ensure reliability and survivability of the power system, so the electric diagrams are simplified: some of the LV bus bars, generators and loads are not illustrated. Moreover, there are several LV levels, e.g. 400 V and 230 V, thus there can be more power transformers in a real maritime distribution network, but they are omitted for simplicity reasons. Also, the grounding method is not shown in the followings.

Fig. 6 shows the simplified power network of a vessel with 2 voltage levels: MV and LV. Each generator is able to supply power for the entire system and the network topology allows reconfiguration. The load shedding technique may be applied if the generated power is exceeded by the consumption. Each load can be powered by each generator using alternative paths for the energy using the appropriate switching of the CBs. For example, if transformer 2 is faulted, then opening of CB42 and closure of the tie-breaker CB34 allows energizing of the bus bar 4 from the bus bar 3.

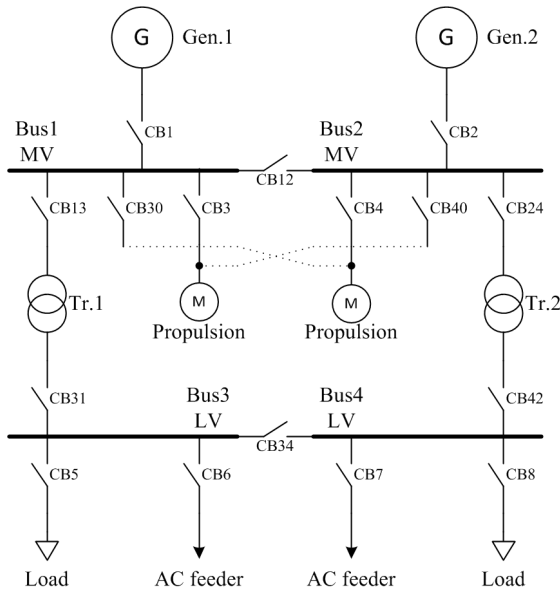


Fig. 6. Simplified marine power system 1

In order to increase the reliability of the vessel, each propulsion system can be switched to another bus bar [16], as shown in Fig. 6 (dotted line). In this case, both propulsion devices can continue to operate even if a bus-bar fault occurs.

Fig. 7 illustrates a more complex marine power system that possesses one additional generator and one additional MV bus bar. In this topology, the MV side of the network allows higher flexibility, as the bus bar 3 and its associated generator can be connected to the bus bar 1, 2 or to both of them by CB13 and CB23. Also, the MV part of the power system is more reliable in the case of a bus bar fault.

Bus bars 4 and 5 are not interconnected by a tie-breaker, but each of them can be powered by 2 different transformers with the primary windings connected to a different MV bus bar, so the survivability condition is fulfilled. In this case, CB41 – CB42 and CB51 – CB52 are interlocked, so the LV bus bars cannot be powered simultaneously from 2 different sources. For example, if transformer 4 fails to deliver power to the bus bar 5, then CB51 and CB52 are complementary switched, ensuring continuity of service. CB8 ensures the continuity of operation for the DC feeders if one of the power converters is tripped.

Fig. 8 presents the simplified power system for an offshore application with the following voltage levels:

- MV level 1 (e.g. 11 kV or 13.8 kV): bus bars 1, 2 and 3
- MV level 2 (e.g. 6.9 kV): bus bars 4, 5, 6 and 7
- LV level (e.g. 690 V or 400 V): bus bars 8 and 9

Due to the survivability requirements, the power system possesses the following characteristics: several distributed generators are used, the energizing of the LV bus bars is possible from 2 different transformers and the MV level 2 bus bars have tie breakers (CB45 and CB67). Moreover, the MV level 1 bus bars form a closed ring, allowing high security in operation against the power outages. However, this topology needs a more advanced protection system, as more CBs need to be operated if a bus bar fault occurs.

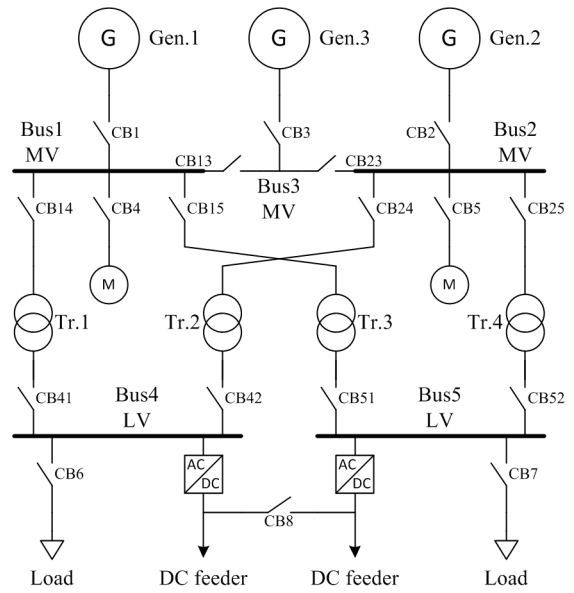


Fig. 7. Simplified marine power system 2

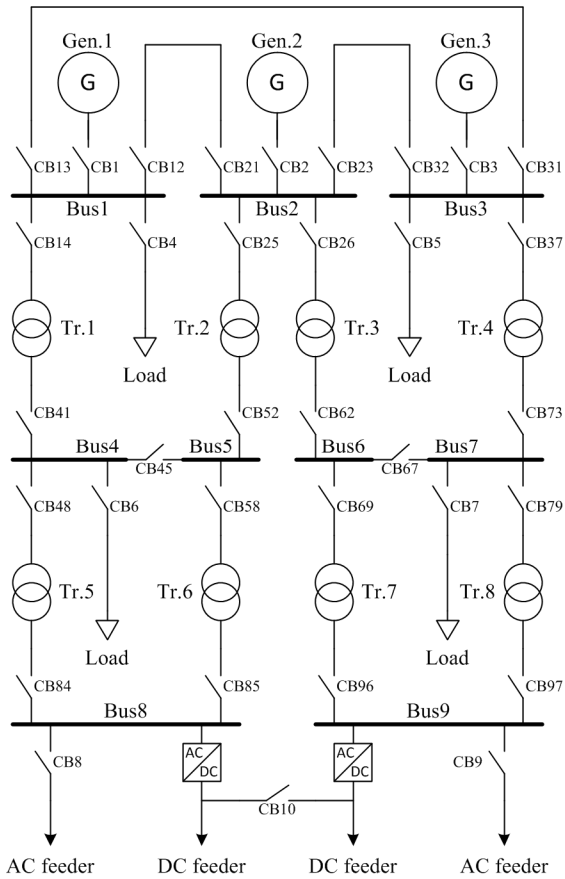


Fig. 8. Simplified offshore power system 1

Generators are placed in different locations of the offshore structure, so the MV level 1 bus bars are inter-connected using cables with various lengths and CBs. This arrangement enhance an improved reliability and security of the power network, as disconnection of a MV level 1 bus bar from another MV level 1 bus bar can be done through 2 different CBs. For example, a fault in the bus bar 2 requires its disconnection from the bus bars 1 and 3, which can be done by CB21 and CB23 or alternately by CB12 and CB32, as a reserve if the first ones fail to operate. CB10 ensures the continuity of operation for the DC feeders if a power converters is tripped.

Fig. 9 presents an offshore power network with increased complexity and additional features, compared to the previous offshore application. The following voltage levels are present within its structure:

- MV level 1 (e.g. 33 kV), composed from the main bus bars (1a and 2a) and the reserve bus bars (1b and 2b)
- MV level 2 (e.g. 11 kV or 13.8 kV): bus bars 3 and 4
- MV level 3 (e.g. 6.9 kV): bus bars 5, 6, 7 and 8

The LV bus bars are powered from the level 2 and level 3 bus bars, but are not shown in this figure. The main generators (Gen.1 and Gen.2) and the power transformers from 1 to 6 can be switched from the main to the reserve bus bars if needed, offering high security against power outages. Moreover, 2 auxiliary generators (Gen.1 and Gen.3) are able to supply power to the MV level 2 bus bars in emergency situations, as power system black start or blackouts.

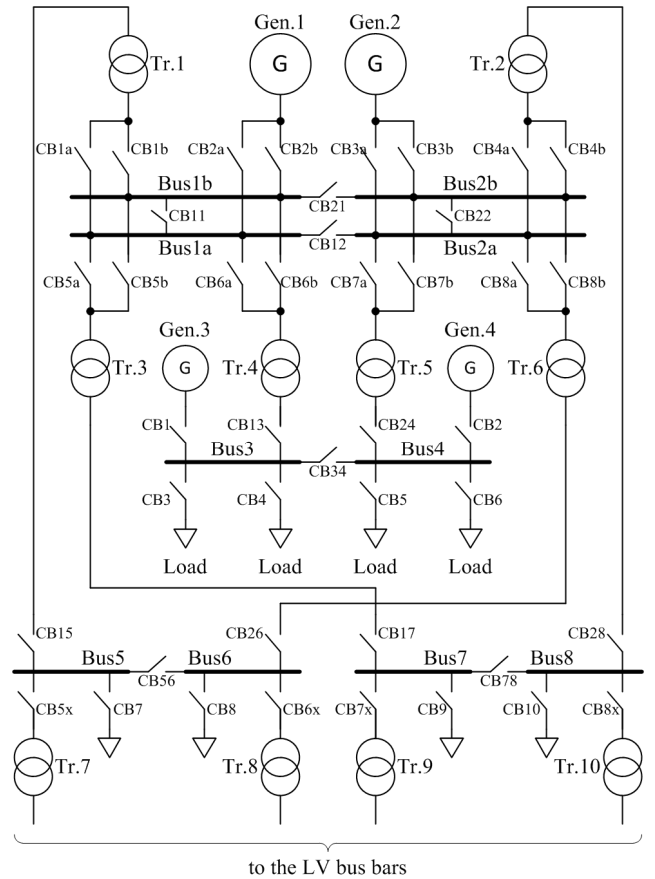


Fig. 9. Simplified offshore power system 2

CB12 and CB21 allow for a single main generator to power the entire network, but load shedding is needed if the generated power is exceeded by the consumption. Also, CB11 and CB22 permit the transfer of power from the main to the reserve bus bars. However, as more CBs need to be controlled and architecture of the network is reconfigurable, the protection system is highly challenged.

IV. PROTECTION PRINCIPLES

A. Protection requirements

Regardless of the solution adopted to protect the previously presented network topologies and to solve the challenges of the maritime applications, any protection system needs to fulfill a set of basic requirements:

- *selectivity*, defined as the ability of the protection system to isolate only the faulted part of the network [1]
- *sensitivity*, defined as the ability of the protection system to detect and react to the smallest unwanted fault [1]
- *simplicity*, as the most simple protection solution that offers the required functionalities is always preferred [15]
- *operation speed*, as the electric faults need to be cleared as soon as possible (times of 100 ms or higher are typical in the MV systems) in order to avoid equipment damage [1]
- *economics*, as the cheapest protection solution that meets the demanded specifications is preferred in industry [15]
- *reliability*, defined as the ability of the protection to operate properly, with 2 aspects: dependability and security [15]

Dependability represents the ability of a protection system to operate correctly in the event of a fault. Security represents the ability of the same protection system to operate correctly in normal conditions or the assurance that it will not trip unless there is a fault. High reliability is typically obtained by optimal design of the protection system and utilization of high quality components for its implementation [1].

B. Structure of the protection system

Regardless of the fault type or network topology, a generic protection system is composed from:

- *monitoring system*, that measures parameters of the electric network, as current, voltage, frequency and phase [1]
- *protective relays*, used to sense the fault conditions based on monitoring and to initiate isolation of the fault [15] [19]
- *CBs*, used to connect or disconnect parts of the network
- *communication infrastructure*, used for coordination and control of the protective relays
- *power source*, providing the energy to the protective equipment [15]
- *other protective devices* that operate remotely (thermal relays, fuses, surge arresters)

Protective relays are part of the protection equipment that have a specific protective function [20] and based on their construction are grouped in [16]:

- thermal (bi-metal) relays
- electromagnetic relays, still used on large scale
- electronic relays, which are dominant today [20]

There is a distinction between 2 types of electronic relays: digital and numerical. The digital protection relays are based on microcontrollers or microprocessors with limited memory and processing capacity, so their functionality is limited to the protective function itself [21]. The numerical protection relays are based on a digital signal processor that offer higher processing capacity and more memory, so more advanced functions are possible [21].

C. Protection techniques

Electrical fault is detected by the protective relays and the affected part of the power system is disconnected by the corresponding CB. Usually, there is a primary protection and a backup (reserve) protection that acts if the first one fails to clear the fault [2]. The maritime applications are no exception from this rule, as the requirements are even more stringent in this sector. The back-up protection is implemented in such way that whatever caused malfunction of the primary protection will not cause failure of its back-up [22].

Protection techniques that are used in land applications are adapted and used in maritime power systems [11]. Among the protection techniques that are used today to protect the power system, can be mentioned:

- *protection coordination or discrimination*, achieved by the inverse and definite time-current relays operating in a coordinated manner [9]
- *zonal protection principle*, achieved by division of the electric network in protection zones, where each zone

corresponds to another protective device and a zonal overlap ensures that there are no unprotected areas [2]

- *differential principle* [9], based on the principle that the current that enters in the protected unit/zone is equal with the current that leaves the protected unit/zone [19]
- *directional protection*, based on detection of the direction of the power flow in an electric circuit [1] [15]
- *symmetrical components*, efficient in detection of the asymmetrical faults [1]
- *additional protective functions*, given by fault locators, insulation monitors and other equipment [23]

Considering the main issues of a maritime power system which are presented in section II, some articles suggest that the protection system needs to be adaptive to the network reconfiguration [4]. Moreover, similar challenges as in the maritime applications are found in the land based MV power systems due to the increased penetration level of distributed generation and the technical solution that deals with them is the adaptive protection [24] [25].

D. Adaptive protection

According to [5], adaptive protection represents the online adjustment of the protection settings in response to the changes of the system status. Usually, adaptive protection implies the existence of a central control unit that monitors the entire power system, changes the relay settings or reconfigures the network [24] [25]. However, the zonal ship design suggests that an adaptive protection using a central control unit needs to be avoided in order to meet the survivability condition. As result, there is a need for new approaches to implement an effective adaptive protection system in maritime applications.

Fig. 10 illustrates the decentralized adaptive protection principle applied to the simplified marine power system 1. The power network is divided in 2 zones and a control unit adjusts the settings of the protective relays from each zone based on the system conditions. The power system monitoring is performed by current/voltage transformers and other sensors, as CB status indicators, that are not shown in the figure. A communication channel allows the information exchange between the 2 protection control units in order to achieve coordination and to ensure that malfunctions in a zone do not affect the protective devices from the other zone.

The same protection principle applies if the power system is more complex or divided in more than 2 zones and several decentralized protection control units are needed. The proposed principle is the subject of the future investigations regarding power system protection in the maritime sector.

V. CONCLUSION

There is a set of specific requirements and challenges that need to be addressed by a protection system in order to be compatible with the maritime sector. Moreover, power system protection needs to be flexible, thus applicable for a wide range of network topologies and applications.

A new protection method that offers similar functionalities as the adaptive protection, but using a decentralized control intelligence is adequate to respond to the needs of the maritime

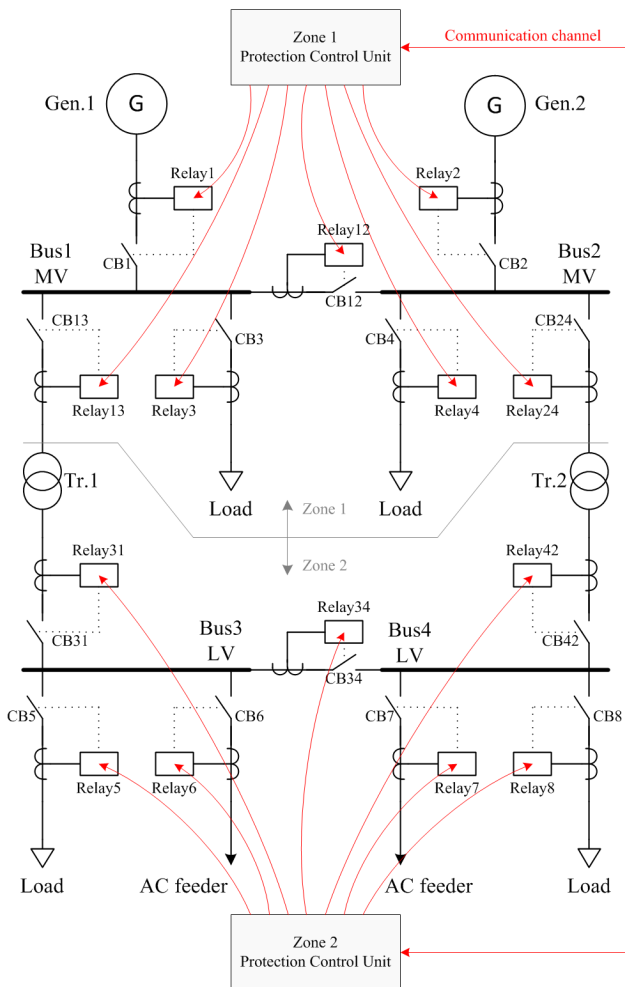


Fig. 10. Decentralized adaptive protection

sector. The following research questions need to be approached in order to develop an intelligent and adaptive power system protection for maritime applications:

1. Is it possible to adapt the protection strategies so that different network topologies of the power system are protected using the same approach?
2. Is it possible for a single protection system to fulfill the entire set of requirements, challenges and issues presented in this paper? How to assess in a realistic manner the performances of protection, as the laboratory work on a real maritime network is excluded in the MV power systems?
3. Decentralized adaptive protection represents the intuitive solution of protection in the maritime sector, but is it possible to distribute the normally seen central intelligence to different protection control units that are spread out in the network, without losing the functionality delivered by a centralized approach?

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