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Abstract — more and more maritime applications as marine vessels and offshore platforms need an adaptive protection power system. However, the adaptive protection is yet to be implemented in the maritime sector. Usually, the adaptive protection implies the existence of a central control unit that monitors the entire electrical network and changes the relay settings accordingly, but this approach is not adequate for the maritime power systems. This paper propose a decentralized adaptive protection method, where each protection relay is able to identify by itself the network status without the need of a central control unit. The new adaptive protection method is based on communication between the overcurrent relays and the equipment that could affect the protection system, such as circuit breakers and generators. Using PSCAD, the proposed method is implemented in a test medium voltage maritime power system that possess some of the characteristics of the maritime applications, as variable generation and network reconfiguration.

Index Terms — adaptive protection, inter-tripping, maritime applications, overcurrent characteristic, protective relays.

I. INTRODUCTION

A set of specific characteristics of the maritime power systems differentiate them from the conventional land based distribution networks. These characteristics are discussed in [1], alongside with the challenges of the protection system in the maritime sector. In brief, the maritime power systems are islanded distribution networks with a radial structure and protected manly by OverCurrent (OC) relays [1]. Security of supply during the fault conditions is achieved by utilization of several distributed generators connected at different bus bars and by reconfiguration of the distribution network so that a load can be powered using various electric paths [1]. However, these features of the power network challenge the protection system, as the fault itself depends on system conditions, thus affecting the fault current seen by the OC relays. Therefore, the maritime applications need a protection system that is adaptive to the network conditions.

The adaptive protection techniques, characterized by online adjustment of the protective relays settings according to network topology and conditions have become more and more popular in the recent years [2]. Several studies proposed different approaches for implementation of an adaptive protection system in different networks in order to solve the protection issues [2]. Authors in [3] suggest utilization of an adaptive protection solution based on communication between a central control unit and the protective relays, where the central control unit monitors the network status and update the relays settings accordingly. However, a central control unit represents a critical point in a network, as its failure may cause problems to the entire adaptive protection system [2]. In addition, the existence of a possible single point of failure is not acceptable in the maritime applications [1]. Other authors suggest an adaptive protection solution where each relay locally detects the network status and based on this information, it selects the appropriate settings [4]. In this way, any problem with a protective relay is limited to that relay only [4]. Nonetheless, this method still needs a communication channel between the component relays and an increased computational power for them. Authors in [5] propose a zonal approach, where a zonal control unit coordinates the relays from its zone. The zone is defined in such way that any modification within its limits require a change of settings only for the protective relays from the affected zone. However, according to [2], this solution is not suitable for the power systems with a reconfigurable topology, including the maritime applications.

The key feature of any adaptive protection system is the ability to acquire relevant information for protection purposes from the electric network and based on it to adjust the relays settings. This feature is possible through communication, but an increased communication burden is a major drawback for any type of protection [2]. Moreover, the communication infrastructure needs to be economically feasible, while the overall protection system needs to be simple and reliable [1].

This paper proposes a decentralized adaptive protection solution based on communication between different relays, Circuit Breakers (CBs) and power generators. Implementation of such communication infrastructure is feasible in the maritime power systems due to the short distance between the

equipment [1]. Moreover, the communication capabilities exist anyway for control purposes in some applications. Only the protection concept is discussed in this paper, while the technical details regarding the communication are not approached. The proposed protection method targets the Medium Voltage (MV) maritime power systems and it is implemented in a test network using PSCAD. In this paper only the 3-phase faults are considered, but the proposed concept is applicable for other types of phase faults as well.

The remainder of this paper is structured as follows. Section II describes the structure and modeling of the test MV maritime network. The proposed protection methodology is explained in details in Section III. Simulation results are presented in Section IV, while Section V concludes this paper.

II. DESCRIPTION OF THE MV MARIMTIME POWER SYSTEM

Fig. 1 illustrates a MV maritime power network in which the proposed adaptive protection solution is tested. It consists of 7 bus bars powered by 3 main diesel generators, represented G_1, G_2 and G_3. Each bus bar feeds a load and the loads connected to *Bus3*, *Bus5*, *Bus7* can also be fed by the emergency generator G_4, if needed. Each generator is able to perform a synchronization operation with the rest of the network. Fig. 1 does not show the electric loads, as well as other components, in order to avoid over-congestion of the diagram. The bus bars are interconnected through several feeders. A feeder consist of a cable, denoted L_{xy}, where *x*, *y* are the indicators of the interconnected bus bars, a transformer for some feeders, represented *Tr.x* and 2 CBs at the both ends of the feeder. Only CB_{12}, CB_{45}, CB_{74} and CB_{75} are shown in Fig.1 as they are used for the network reconfiguration.

The standard models available in PSCAD for the internal combustion engine and synchronous machine are used to model the diesel generators based on the parameters given in TABLE I. The power transformers are also modeled using the standard models available in PSCAD based on the parameters given in TABLE II. The electric cables are modeled using the π-model and the electric loads are modeled as constant impedances. TABLE III and TABLE IV give the cables data and the consumed power at the rated voltage for each load.

As mentioned previously, some CBs are used not only to disconnect a faulted section from the rest of the network, but also to reconfigure the power system. For example, CB_{45} allows the power transfer from *Bus4* to *Bus5* or opposite, if needed. However, CB_{45} never closes as long as both *Bus4* and
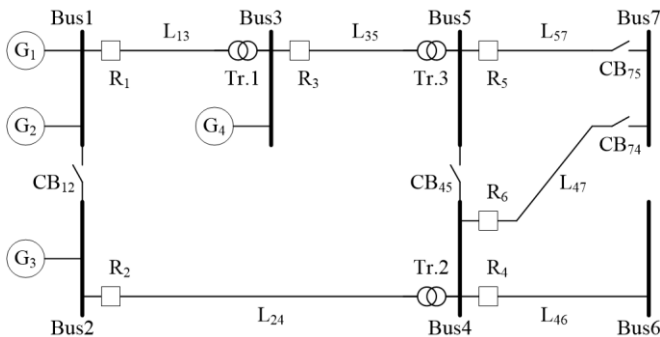

Fig. 1. Test MV maritime power system

TABLE I. Diesel Generators Data

Parameters	G_1, G_2, G_3	G_4
Synchronous machine		
Rated power [kVA]	3600	2400
Rated voltage [kV]	11	6.6
Rated frequency [Hz]	50	50
Stator resistance [p.u.]	0.01	0.015
Stator reactance [p.u.]	0.11	0.08
d-axis synchronous reactance [p.u.]	1.80	1.65
d-axis transient reactance [p.u.]	0.275	0.225
d-axis subtransient reactance [p.u.]	0.185	0.145
q-axis synchronous reactance [p.u.]	1.15	1.15
q-axis subtransient reactance [p.u.]	0.205	0.195
d-axis transient time [s]	0.55	0.42
d-axis subtransient time [s]	0.08	0.06
q-axis subtransient time [s]	0.08	0.06
Inertia constant [s]	2.0	1.5
Neutral series resistance [Ω]	320	190
AC exciter type [a]	AC1A	AC1A
Internal combustion engine		
Rated output power [kW]	3000	2000
Rated speed [rpm]	1500	1500
Gearbox ratio	1	1
Gearbox efficiency	0.98	0.98
Regulator type	PI	PI
Regulator proportional gain	12.5	12.5
Regulator integral time constant [s]	0.075	0.075
Regulator output upper limit	1.2	1.2
Regulator output lower limit	0	0

a. Parameters of the AC1A exciter used in this paper are given in [6]

TABLE II. Power Transformers Data

Parameters	Tr.1	Tr.2	Tr.3
Rated power [kVA]	2000	2000	2000
Primary voltage [kV]	11	11	6.6
Secondary voltage [kV]	6.6	3.3	3.3
Copper losses [p.u.]	0.011	0.01	0.0105
Iron losses [p.u.]	0.00175	0.002	0.00175
Short-circuit impedance [p.u.]	0.06	0.06	0.06
No-load current [%]	1	1	1.1
Vector group	Dyn5	Dyn5	Dyn5
Neutral series impedance [Ω]	190	95	95

TABLE III. Electric Cables Data

Cable	Resistance [mΩ]	Inductance [µH]	Capacitance/2 [nF]
L_{13}	52.4	37.6	29.3
L_{24}	10.48	7.52	5.86
L_{35}	26.8	33.1	37.1
L_{46}, L_{57}	14.54	7.94	5.22
L_{47}	36.35	19.85	13.05

TABLE IV. Load Data

Load on	Rated voltage [kV]	Consumed power [kVA]	Power factor
Bus1, Bus2	11	2236	0.88
Bus3	6.6	894	0.89
Bus4, Bus5	3.3	335	0.91
Bus6, Bus7	3.3	335	0.92

Bus5 are already energized. Similarly, CB_{74} and CB_{75} are logically interlocked so that *Bus7* is energized from *Bus4* or *Bus5*, but not from both simultaneously.

Each feeder of the test MV maritime power systems is protected by an OC relay R_x, where *x* is the indicator of the feeding bus bar. Fig. 2 presents the arrangement of the OC relays, Current Transformers (CTs) and CBs for 2 generic feeders. When an OC relay trips, it sends a signal to the 2 CBs placed at the both ends of its corresponding feeder. The same 2 CBs are also used to disconnect the feeder from the network in order to reconfigure the power system or to allow the maintenance operations. In the followings, the 2 CBs placed at the booth ends of a feeder are referred as CB_{xy} and CB_{yx}, where *x* and *y* are the indicators of the bus bars interconnected by that feeder.

III.   PROPOSED METHODOLOGY

The main purpose of the proposed adaptive protection algorithm is to achieve proper coordination of the OC relays and clearance of the fault as fast as possible. As mentioned in Section I, the new adaptive protection concept is based on the communication network between different equipment. Each relay is able to obtain online information about the status of the generators or CBs position, thus to correctly identify the network status. The relays are also able to communicate with each other. Each relay is provided with 2 protection functions: an OC protection and an inter-tripping function that allows to a relay to stimulate the tripping operation of another relay. The inter-tripping function is based on communication between the relays. Both functions are dependent on the network conditions and are described in the followings.

A.   OverCurrent function

The OC protection function consists from a definite time delay function and an inverse time delay function. The pick-up current I_P^{DTD} for the definite time delay OC protection is set in such way that the bolted faults within the relay's protection zone are cleared after a definite time delay. In this paper, the definite time delay is set to *40 ms* and it accounts for operation of the physical relays. The pick-up current I_P^{ITD} for the inverse time delay OC protection is set to 1.5 times the nominal current seen by the relay in normal conditions. The IEC very inverse characteristic is selected to obtain the inverse time delay based on the mathematical expression given in (1).

$$t_{ITD} = TMS \cdot \left[\frac{k}{\left(\dfrac{I}{I_P^{ITD}} \right)^{\alpha}} + c \right] \qquad (1)$$
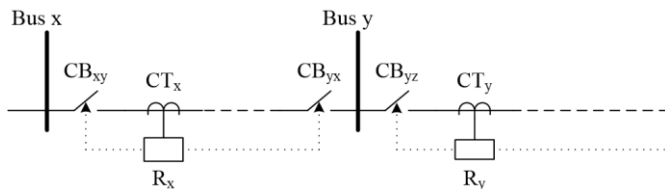
t_{ITD} is the operating time (inverse time delay) of the relay, *TMS* is the Time Multiplier Setting, *I* represents the actual current seen by the relay and *k*, *c*, *α* are constants whose values are respectively *13.5*, *0*, *1* for the IEC very inverse characteristic [7]. *TMS* is selected in such way that the relay provides backup protection with sufficient margin time for the faults that are not cleared by the downstream relays.

An offline analysis of the power system is performed in order to compute the proper settings of the OC protection relays (I_P^{DTD}, I_P^{IDT} and *TMS*) for each possible status of the network. Each relay stores the calculated settings in its internal memory, but only a single set of settings is active at once. Selection of the active settings is realized based on the network status detected by the relay. The relay continuously adjusts the OC settings, so that the optimal OC settings are always active. The discussed adaptive protection algorithm is presented in Fig. 3.

B.   Inter-tripping function

As mentioned in the previous section, each OC relay provides backup protection for the electrical faults located outside its protection zone in the event that the primary protection suffer a failure. However, the time needed by the primary protection to clear such faults can be relatively long in some cases. The damage produced to the electrical equipment is proportional with the fault current and the fault duration, so a decrease of the trip time can reduce the equipment damage and the danger to which the personnel is exposed [8].

Malfunction of the primary protection system can be caused by a failure of its corresponding CBs to interrupt the fault current. In order to mitigate the negative effects of the fault in this situation and to limit the equipment damage, an inter-tripping function is implemented for each OC relay. More specifically, if a relay trips, but its corresponding CBs

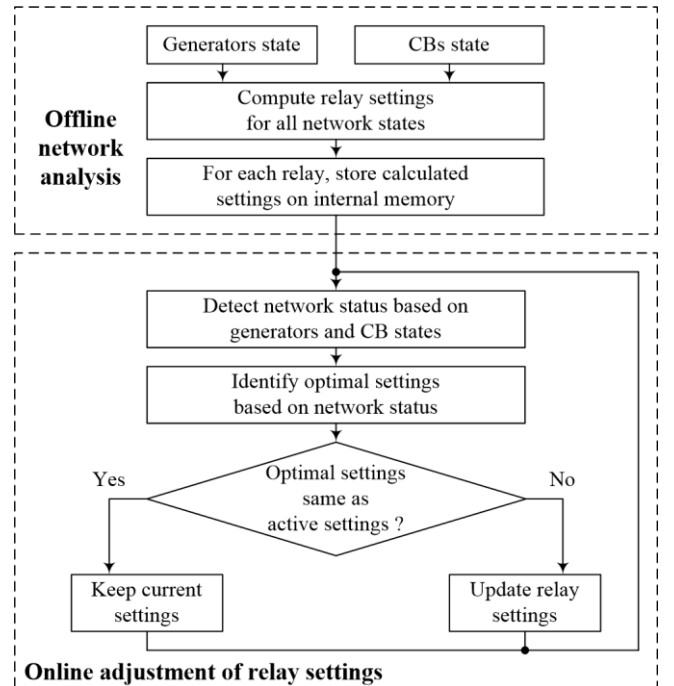Fig. 2. Arrangement of the protection equipment for a generic feeder

Fig. 3. Adaptive OC protection algorithm

fail to clear the fault, the same relay sends an inter-trip command to the nearest OC relay placed upstream. The inter-trip command overrides the OC function of the upstream relay and impels it to trip instantaneously.

Considering Fig. 2, if R_y trips, but CB_{yz} fails to open within a certain timeframe, R_y sends the inter-trip command to R_x, which trips instantaneously, thus clearing the fault on the downstream feeder. There is chance that R_x would have tripped anyway due to its inverse time characteristic, but not as fast as using the inter-trip function. The timeframe between the moment when a protection relay trips and it sends the inter-trip signal to another relay should be longer than the time needed by a CB to operate. In this paper, this time interval is set to *200 ms*.

The inter-tripping function is adaptive to the network status because for a given relay, its nearest upstream relay could be different for different configurations of the power system. For example, in Fig. 1, the nearest upstream relay for R_5 could be R_2 or R_3, depending on the status of CB_{45}. Note that the inter-tripping function is effective only against a malfunction of the CB, as it cannot operate if the OC protection function of the relay is defective. Moreover, the inter-tripping function still needs the proper relay coordination that is provided by the adaptive OC protection algorithm.

IV. SIMULATION RESULTS

The proposed adaptive protection method is compared with a traditional OC protection approach using the test MV maritime network. The performance of the 2 protection methods is evaluated using a 3-phase bolted fault applied on the primary side of *Tr.3*. For both protection methods, the arrangement of the relays is identical and as it is described in Section II, but for the traditional OC protection approach, the relay settings are not adaptive. To challenge these 2 protection systems, 3 different states of the test MV network are considered. The fault is applied successively for each state of the test MV network and for each protection system.

Status of the test MV power system is determined by the operating generators and by CBs status. For each network state, those power generators that are connected to the network and those CBs that are open are presented in TABLE V. *Status 1* represents the normal configuration of the MV network. The relay settings for the traditional OC relays are computed based on this network state. *Status 2* represents the MV network with the same configuration as in *Status 1*, but powered by 3 main generators, so an increased short-circuit power is available during the fault. In *Status 3*, the feeder corresponding to R_1 is disconnected, so *Bus3*, *Bus5* and *Bus7* are powered by the emergency generator and the available short-circuit power for these bus bars is reduced compared to the previous states of the network.

TABLE V. Analyzed States of the Test MV Maritime Power System

Network Status	Operating generator	Open CBs
Status 1	G_1, G_3	CB_{45}, CB_{74}
Status 2	G_1, G_2, G_3	CB_{45}, CB_{74}
Status 3	G_1, G_2, G_4	CB_{45}, CB_{74}, CB_{13}, CB_{31}

The relay settings of the adaptive protection method for all states of the test MV power system are obtain from the offline network analysis. Settings of the traditional OC protection and the active settings of the adaptive OC protection for *Status 1* are identical. The time-current curves of the adaptive protection system for different states of the test MV network for R_1, R_3 and R_5 on 3.3 kV base are given in Fig. 4 and their corresponding settings are presented in TABLE VI.

Due to the location of the applied fault on the primary side of *Tr.3*, the fault needs to be cleared by R_3, while R_1 is to provide backup protection for R_3. Moreover, as the considered fault is a 3-phase bolted fault within the protection zone of R_3, it is desirable for this relay to trip with the definite time delay (set to *40 ms*). Acting as a backup, R_1 should trip if R_3 fails to

a) Time-current curves for Status 1

b) Time-current curves for Status 2

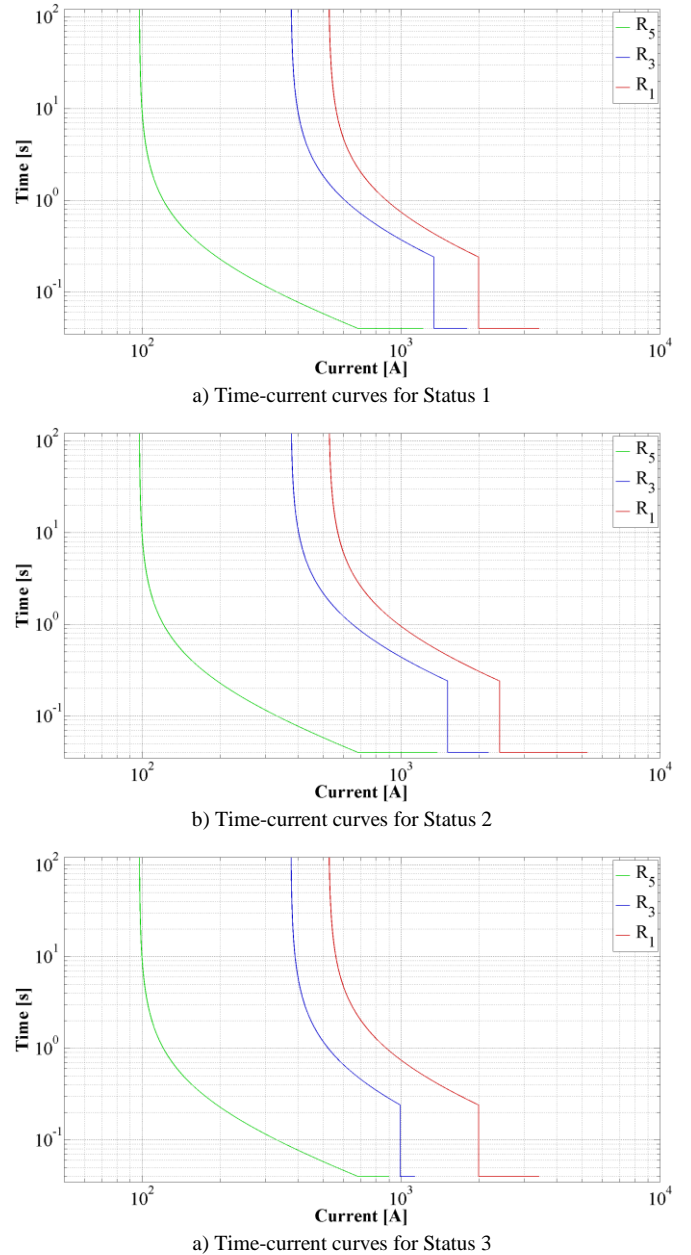a) Time-current curves for Status 3

Fig. 4. Time-current curves (on 3.3 kV base) of adaptive protection system for different states of the test MV maritime network for R_1, R_3 and R_5

TABLE VI. Relay settings of the adaptive protection system for different states of the test MV maritime network for R_1, R_3 and R_5

System status	Relay	I_P^{DTD} [A]	I_P^{IDT}	TMS
Status 1	R_1	1995	525	0.0498
	R_3	1341	375	0.0458
	R_5	682.5	97.5	0.0178
Status 2	R_1	2407	525	0.0637
	R_3	1517	375	0.0541
	R_5	682.5	97.5	0.0178
Status 3	R_1	1995	525	0.0498
	R_3	994.5	375	0.0294
	R_5	682.5	97.5	0.0400

TABLE VII. Operating times of the protective relays for traditional OC protection and adaptive OC protection for different states of the MV network

Network status	Relay operating time [ms]			
	Traditional OC protection		Adaptive OC protection	
	R_1	R_3	R_1	R_3
Status 1	276	40	276 (240)	40
Status 2	40	40	273 (240)	40
Status 3	-	308	-	40

clear the fault, but with a sufficient time margin (set to *200 ms*) in order for the protection system to be selective. The other relays are unable to sense the applied fault, so only the tripping signals of R_1 and R_3 are relevant in this situation.

Simulation results for R_1 and R_3, for the traditional and adaptive protection systems for the considered states of the test MV network are presented in TABLE VII. Note that for the adaptive OC protection, there are 2 times for R_1: the values on parentheses represent the operating times if the inter-tripping function is active and the other values represent the operating times with the inter-tripping function disabled.

Both protection systems perform similarly for *Status 1* of the network. However, for the other 2 network states, the adaptive protection system is superior. For *Status 2*, the adaptive protection method behaves as intended: R_3 operates in *40 ms* and the operating time of R_1 is sufficient to fulfill the selectivity condition. The traditional OC protection is not selective for *Status 2*, as R_1 and R_3 operate simultaneously. Of course that the traditional OC protection can be graded in such way that it will be selective for *Status 2*, but then its behavior will not be optimal for *Status 1*. For *Status 3*, the fault current is provided by G_4, thus R_1 is not affected in this case. The adaptive protection system operates in *40 ms*, while it takes *308 ms* to the traditional OC protection to operate.

The inter-tripping function shortens the operating times of a relay if its backup function is needed, but not beyond the selectivity margin, as it can be observed in TABLE VII for *Status 1* and *Status 2*. The difference between the operating time of R_1 with a disabled inter-tripping function and with an active inter-tripping function is *36 ms* for *Status 1* and *33 ms* for *Status 2*. Considering that another *200 ms* are needed for a CB to interrupt the fault current, it results that the inter-tripping function reduces the overall clearance time of a backup OC relay with about *8%* in the simulated conditions.

V. CONCLUSIONS

The protection systems in the MV maritime networks are challenged by several factors, including variable generation and network reconfiguration. Therefore, the traditional OC protection techniques are not capable to perform optimal for the entire set of network states and the protection selectivity could be lost in some cases. Consequently, the protection system needs to be adaptive to the network status, but

simultaneously, a centralized approach for an adaptive power system should be avoided in the maritime sector.

A decentralized adaptive protection system based on communication between the OC relays, CBs and generators is proposed in this paper. The communication infrastructure is needed and sometimes already existent in the maritime applications for control purposes. Therefore, implementation of the proposed protection method is feasible from technical and economic points of view in maritime MV power system. The novelty of the proposed adaptive protection system is the absence of a central control unit, as each relay is able to acquire information from the network equipment, with the advantage that a possible single point of failure is eliminated.

Additionally, an inter-tripping function of the OC relays is suggested in order to improve the backup operation of the protection system. The cost of such function is reduced because it does not require any additional hardware and it is based on the same communication infrastructure as the proposed adaptive protection method.

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