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Ciontea, Catalin-Iosif; Bak, Claus Leth; Blaabjerg, Frede; Madsen, Kjeld Kilsgaard; Sterregaard, Claes Høll

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Fault Analysis for Protection Purposes in Maritime Applications

C.I. Ciontea[1,2], C. Leth Bak[1], F. Blaabjerg[1], K.K. Madsen[2], C.H. Sterregaard[2]

[1]Department of Energy Technology, Aalborg University, Denmark, [2]DEIF A/S, Denmark
E-mail: [1,2]cic@et.aau.dk

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Abstract

The method of symmetrical components simplifies analysis of a three-phase network and provides information regarding the existance of a fault in the system. This concept is applied to a radial power system in the maritime sector. A fault analysis is performed for the main types of faults, applied in different locations of the network. The fault current is measured using the curent transformers that are already present in the system as part of a time-inverse overcurrent protection. Simulation results show that the symmetrical components of the currents seen by these current transformers can be used to detect the electric fault. The method also provides an improved fault detection over the conventional overcurrent relays in some situations. All results are obtain using MATLAB/Simulink and are briefly discussed in this paper.

1 Introduction

The need of automatic protection is as old as the first power system ever installed and one of the first solutions to the electric fault problem is based on the response of protective elements to the excess current. Most of the power networks are protected by overcurrent protection, achieved by fuses, by direct acting trip mechanism on Circuit Breakers (CBs) and by protective relays [1]. However, complexity of the power systems operating today needs more advanced protection techniques in order to ensure the adequate discrimination. As result, apart from the overcurrent criteria, other techniques are used to detect the fault conditions: the differential principle, monitoring of the power direction, the impedance variation, deviation of the voltage or frequency and others [2].

Maritime applications are characterized by specific challenges and requirements [3] and represent an interesting topic in terms of network protection. According to [3], majority of the maritime applications can be regarded as radial networks. The overcurrent protection is widely used in such systems in combination with other types of protection, if needed. For example, the differential protection can be used to protect generators against the internal faults, while the directional element is useful when parallel feeders are involved [4]. The aim of combining several methods of protection is to ensure selectivity and dependability of the protection system.

Fig. 1 presents a typical radial feeder that is part of a maritime power network. It is fed by the source *G* and protected by the time-inverse overcurrent relays *R1*, *R2* and *R3*. They operate in a time inversely proportional to the fault current [5], but only if a minimum current, known as the pickup current, is exceed [6]. Moreover, there is a minimum operating time for the currents above a certain level [7] and coordination of such relays is achieved by proper grading. Each element protects a primary zone of protection and offers backup protection for the downstream zones to the extent within the range of the relay permits [8]. The maximum range that can be protected by an overcurrent relay is referred as the relay's reach [6].

Selection of the appropriate protective elements and correct grading of the overcurrent relays require an initial analysis of the network that needs to be protected. In power systems, the method of symmetrical components is used to simplify the analysis of a circuit in both normal and fault conditions. In protection, the same method can be used in grading procedure of the overcurrent relays. Also, it is used as a discrimination criteria between the normal and some abnormal conditions [9]. For example, the asymmetric faults and the asymmetric network conditions can be detected by monitoring of the symmetrical components of the voltage or current [2].

Based on these prerequisites, this paper investigates to what extent the method of symmetrical components gives useful information for protection of a typical radial feeder in the maritime sector. More precisely, a correlation between the abnormal conditions and the symmetrical components of the current is sought. The correlation may be given by a threshold magnitude of a specific sequence set or by a specific ratio between the sequence sets. More than that, only the currents accessible by the CTs corresponding to the overcurrent relays are used. In this way, the conventional overcurrent protection could be improved, while the monitoring system remains the same. In this purpose, a comprehensive analysis of a maritime power network in different abnormal conditions is performed and the fault currents are examined using the method of symmetrical components. The entire analysis is conducted using MATLAB/Simulink and PLECS library, where the power network and electric faults are implemented.

This paper is structured as follows. In section 2, the method of symmetrical components and its fault detection principles are presented. Section 3 describes the structure of the power network that is studied, including the location and the types of the faults. Simulation results are presented and discussed in section 4, followed by the conclusions in section 5.

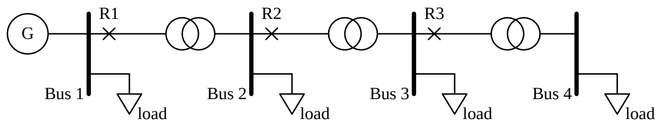

Fig. 1: Typical radial feeder

2 Fault analysis based on Fortescue's theorem

2.1 Method of symmetrical components at glance

The method of symmetrical components is based on the Fortescue's theorem that states that any set of *m* unbalanced phasors can be represented by the sum of 3 sets of *m* balanced phasors: the *positive-sequence* set, the *negative-sequence* set and the *zero-sequence* set [10]. For the unbalanced set of currents in a three-phase power system, their corresponding sequence components, referred to *phase a*, are given by (1).

$$\begin{bmatrix} I_{1a} \\ I_{2a} \\ I_{0a} \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (1)$$

where I_a, I_b, I_c are the phase currents, I_{1a}, I_{2a}, I_{0a} are the positive, negative, respectively zero-sequence components of the phase currents and a is a unit phasor with an displacement of 120° [10], shown in (2).

$$a = 1\angle 120° = -\frac{1}{2} + j \cdot \frac{\sqrt{3}}{2} \quad (2)$$

Relations between the symmetrical components referred to the *phase a* and the symmetrical components referred to the other phases are given by (3) and (4).

$$\begin{bmatrix} I_{1b} & I_{2c} \\ I_{1c} & I_{2b} \end{bmatrix} = \begin{bmatrix} a^2 \\ a \end{bmatrix} \cdot \begin{bmatrix} I_{1a} & I_{2a} \end{bmatrix} \quad (3)$$

$$I_{0a} = I_{0b} = I_{0c} \quad (4)$$

The positive-sequence set phasors have equal magnitudes, are symmetrically spaced at 120° intervals and have the same phase sequence as the initial currents. The negative-sequence set phasors have equal magnitudes and are symmetrically spaced at 120° intervals, but have a reversed phase sequence compared to the initial current. Finally, the zero-sequence set phasors are equal in both magnitude and phase and rotate similar to the positive-sequence set [9]. It is usual to perform the analysis of the symmetrical components based on a single reference phase, commonly the *phase a*. This permits to the phase subscription to be omitted, as it is understood that the quantities referred to are always the reference phase values [9]. Hence the phase subscript is omitted in the followings.

The symmetrical components of a three-phase voltage system can be determined similarly, using (1) – (4). Furthermore, using the Ohm's law, the impedances of the symmetrical components can be determined [11], as shown in (5).

$$Z_n = \frac{U_n}{I_n}, \quad n = 0,1,2 \quad (5)$$

where U_0, U_1, U_2 are the symmetrical components of the voltage and Z_0, Z_1, Z_2 are the zero, positive, respectively negative-sequence impedances. It is also possible to define equivalent circuits for each sequence set, as [7] presents.

2.2 Symmetrical components of the fault current

Synchronous Generators (SG), as the main source of electric power in both land and maritime applications, are designed to generate only positive-sequence currents. Contrariwise, the negative-sequence and the zero-sequence quantities exist only in the asymmetric conditions or unbalanced networks [10]. As the generated currents are only positive-sequence by design, the negative and the zero-sequence sets are generated at the point of asymmetry. Moreover, there is a relation between the symmetrical components of the fault current and the abnormal condition [5]. Table 1 presents the symmetrical components of the currents at fault location for the main types of bolted faults. The negative-sequence set only appears during the asymmetric faults, the zero-sequence set only appears during the ground faults, while the 3-phase fault is symmetric, so only the positive-sequence set exists in this case [2].

Another abnormal condition that is not desired in a power system is the interruption of the phase conductor. Such condition is dangerous especially for delta connected motors, causing increased currents in the windings, whilst the phase currents seen by the overcurrent relay are below the pickup value [12]. The boundary conditions for the currents in a circuit where a phase conductor is interrupted are given in (6).

$$I_a = 0, \; I_b = -I_c \quad (6)$$

From (1) and (6), after calculations, the relation between the symmetrical components of the current for an interrupted conductor are obtained in (7). It shows that in such condition, the zero-sequence currents are not present, while the positive and the negative-sequence sets are equal in magnitude.

$$I_1 = -I_2, \; I_0 = 0 \quad (7)$$

2.3 Detection of the abnormal conditions

Examination of the fault current using the method of symmetrical components gives information regarding the presence of an abnormal condition in a power system. Table 2 summarizes the abnormal conditions addressed in this paper and presents the dependencies between the symmetrical components of the fault current for each type of fault. They represent the basis for detection of the electric fault in a power system using the method of symmetrical components.

Fault type	I_1	I_2	I_0
3-phase	$\frac{E}{Z_1}$	0	0
2-phase	$\frac{E}{Z_1+Z_2}$	$\frac{-E}{Z_1+Z_2}$	0
2-phase to ground	$\frac{(Z_2+Z_0)\cdot E}{Z_{eq}}$	$\frac{-Z_0\cdot E}{Z_{eq}}$	$\frac{-Z_2\cdot E}{Z_{eq}}$
1-phase to ground	$\frac{E}{Z_1+Z_2+Z_0}$	$\frac{E}{Z_1+Z_2+Z_0}$	$\frac{E}{Z_1+Z_2+Z_0}$
E = *voltage of the source* $\quad Z_{eq} = Z_1 \cdot Z_2 + Z_1 \cdot Z_0 + Z_2 \cdot Z_0$			

Table 1: Symmetrical components of different fault currents [2] [9]

Fault type	Symmetrical components
3-phase (3ph)	$I_1 \neq 0$ $\quad I_2 = I_0 = 0$
2-phase (2ph)	$I_1 = -I_2$ $\quad I_0 = 0$
2-phase to ground (2ph-g)	$I_1 = -I_2 - I_0$
1-phase to ground (1ph-g)	$I_1 = I_2 = I_0$
1-phase open circuit (1ph-oc)	$I_1 = -I_2$ $\quad I_0 = 0$

Table 2: Mathematical dependencies of positive, negative and zero-sequence sets of the fault current at fault location for different fault conditions

The mathematical relations given in Table 2 are valid only for the fault currents, which are not accessible because in most situations the fault occurs far from the CTs location. Actually, the currents measured by the CTs during the fault conditions have 2 components, as evidenced in Fig. 2: one component maintains the electric fault and the other component supplies the healthy parts of the network. However, the symmetrical components of the currents seen by the CTs could provide information regarding the sequence sets of the fault currents, thus information regarding the fault itself.

3 Maritime power system description

3.1 Overview of the power system under study

Fig. 3 illustrates a simplified maritime power network whose currents are measured by the indicated CTs and analysed using the method of symmetrical components for the faults applied at the locations displayed. Due to the nature of the maritme applications, such power systems are reconfigurable, so in fault conditions it provide continuous supply for the essential loads [0]. Reconfiguration of the power network is possible using various CBs, so each bus bar can be energised using an alternative path for energy. For example, Bus bar 4 is powered by Transformer 24 or by Bus bar 3, but not by both simulataneously. Reconfiguration of the system changes the current seen by the CTs [13], so this study is conducted for several configurations of the network. Only the CBs that are relevant for these configurations are shown in Fig. 3 and their status is presented in Table 3.

3.2 Modeling of power system components

Modeling of the components of the maritime power system is presented in Fig. 4 and the models are discussed briefly in this section. The network is fed by a SG that is modeled as an ideal voltage source and a series impedance, $R_{gen} + j{\cdot}X_{gen}$, calculated in (8) according to its parameters. Grounding of the generator is realised through a 400 Ω resistor.

$$R_{gen} = \frac{X_{gen}}{X\,/\,R_{ratio}}, \quad X_{gen} = X_s \cdot Z_{base} \qquad (8)$$

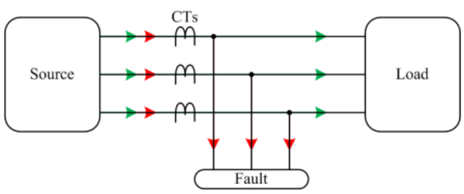

Fig. 2: CTs current composition: load current (green) + fault current (red)

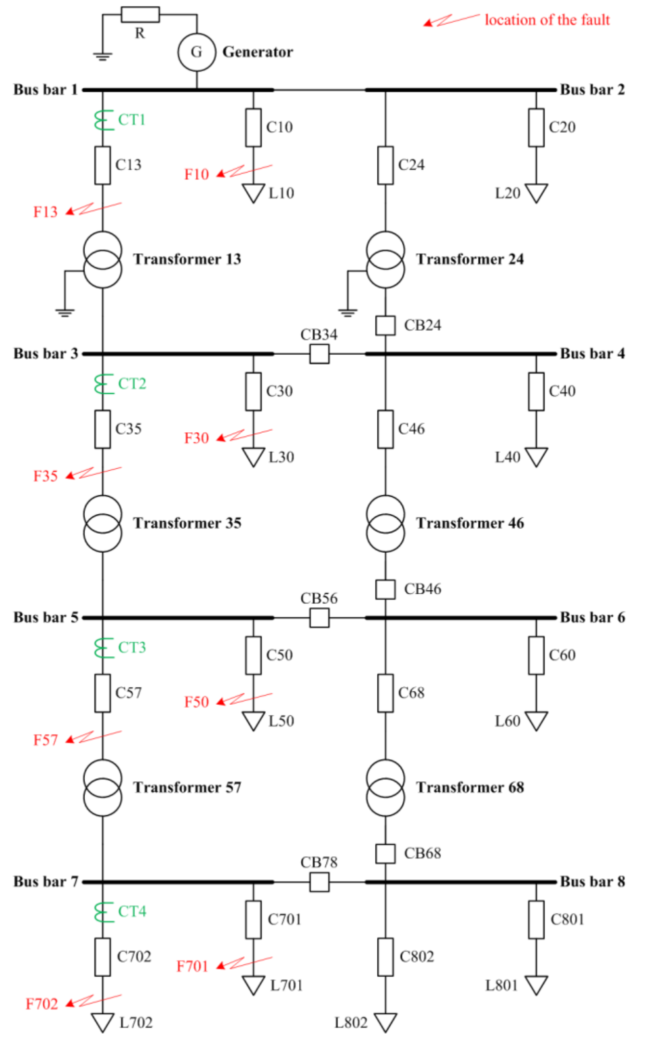

Fig. 3: Overview of the maritime power network

X_s is the synchronous reactance of the SG relative to the base impedance Z_{base}. The base impedance is calculated in (9) based on parameters given in Table 4. V_{gen} and S_{gen} denote the rated voltage, respectively the rated power of the generator.

$$Z_{base} = \frac{V_{gen}^2}{S_{gen}} \qquad (9)$$

The power transformers are modeled by an ideal transformer accounting for the transformer's ratio and a series equivalent impedance, $R_{traf} + j{\cdot}X_{traf}$, calculated in (10), based on the parameters given in Table 4 [11]. Transformer 13 and 24 (Dyn5 vector group) are directly grounded, whilst the other transformers are not grounded (Dd vector group).

Network configuration	CBs status	
	CBs closed	CBs open
config. 1	CB24, CB46, CB68	CB34, CB56, CB78
config. 2	CB34, CB46, CB68	CB24, CB56, CB78
config. 3	CB24, CB56, CB68	CB34, CB46, CB78
config. 4	CB24, CB46, CB78	CB34, CB56, CB68

Table 3: Configurations of the network and corresponding status of the CBs

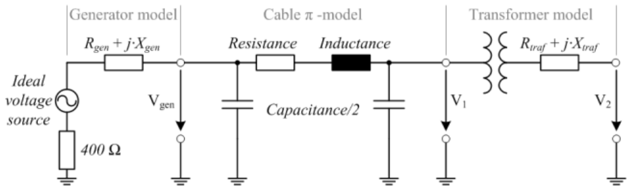

Fig. 4: Modeling of the main components of the power system

$$R_{traf} = \frac{P_{Cu} \cdot V_2^2}{S_{traf}^2}, \quad X_{traf} = \frac{v_{sh} \cdot V_2^2}{S_{traf}} \tag{10}$$

V_1 and V_2 denote the primary, respectively the secondary voltage, S_{traf} is the rated power, v_{sh} represents the short-circuit voltage and P_{Cu} are the copper losses of the transformer.

Cables used in the network are modeled using the π-model, and the electric loads are modeled as constant impedances with a unity power factor. Parameters of the cables and the consumed power at the rated voltage for each phase are given in Table 5. Measurement of the currents is realized by ideal CTs and symmetrical components are determined using the standard calculation blocks of MATLAB/Simulink.

4 Simulation results

4.1 Symmetrical components in no fault conditions

Symmetrical components of the currents measured by the suggested CTs for different network configurations in no fault conditions are presented in Fig. 5. The zero-sequence set is zero in all cases because there is no abnormal condition in the system, thus its corresponding figure is not displayed. The bars corresponding to *rated* are calculated and represent the values of the sequence-sets when each transformers is loaded with the rated balanced current. Also, their magnitudes are displayed on top of the bar because they serve as a basis for comparison of the fault currents. The other bars represent the sequence currents in normal conditions for the considered configurations of the maritime power system. Existence of the negative-sequence current is due to the unbalanced loads. As result, it needs to distinguish between the negative-sequence currents produced by the faults and the negative-sequence currents produced by the unbalanced conditions.

Fig. 5 shows the range of variation of the current seen by each CT as a function of network's configuration and highlight the need of adaptive relay settings. For example, CT3 measures a current that is almost double for *config.4* compared to the other configurations. Therefore, the pickup current of the overcurrent relays, assuming that the feeder is protected in such way, needs to be changed accordingly.

Name	V_{gen} [kV]	S_{gen} [kVA]	X_s [p.u.]	X/R ratio
Generator	13.8	12 500	1.5	50
Name	V_1/V_2 [kV]	S_{traf} [kVA]	v_{sh} [%]	P_{Cu} [kW]
Tr.13, Tr.24	13.8/6.9	2 000	6	21
Tr.35, Tr.46	6.9/0.4	500	6	10.5
Tr.57, Tr.68	0.4/0.23	200	4	2.8

Table 4: Main parameters of the generator and power transformers

Name	Resistance [mΩ]	Inductance [uH]	Capacitance/2 [nF]
C13, C24	38.7	35.0	16.25
C35, C46	72.7	39.7	13.05
C57, C68	12.4	29.4	24.85
C10, C20	9.68	8.75	4.06
C30, C40	18.18	9.93	3.26
C50, C60	3.4	7.35	6.21
C701,702,801,802	13.1	9.4	3.66
Name	Power [kW] phase a	Power [kW] phase b	Power [kW] phase c
L10, L20	1 333	1 333	1 333
L30, L40	250	250	250
L50	50	50	50
L60	33	50	33
L701, L702, L801	15	15	15
L802	10	15	10

Table 5: Parameters of the cables and the consumed power by the loads

4.2 Symmetrical components for faults on the feeder

Symmetrical components of the currents seen by the CTs of the maritime network in configuration 1 for different faults located on the feeder (F13, F35, F57 and F702) are illustrated in Fig. 6. For every CT, the magnitude of each current is expressed in per units of the rated positive-sequence set for that CT. The faults that are characterized by currents higher than the pickup current of a conventional overcurrent relay can be detected by it. The pickup current is set to let's say *1.25 p.u.* of the rated current in the protected circuit. As result, examination of Fig. 6a shows that the faults involving minimum 2 phases can be detected based on observation of the positive-sequence set magnitudes, which are higher than the typical pickup current in at least one CT location. The same is valid for the 1-phase to ground fault in location F35.

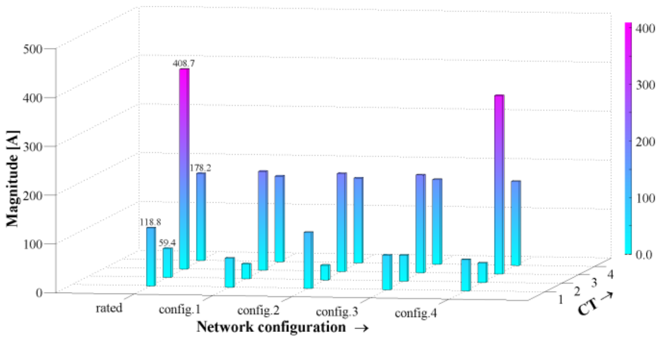

Fig 5a: Positive-sequence set in normal conditions

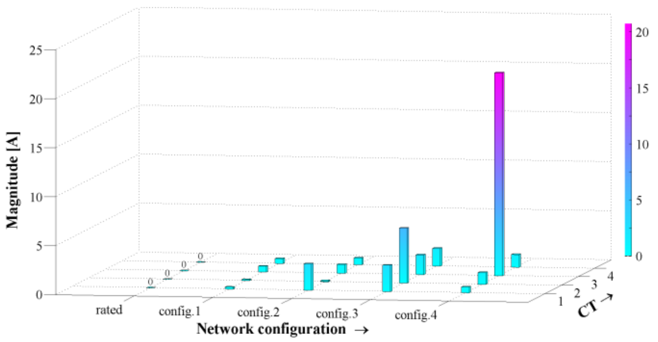

Fig 5b: Negative-sequence set in normal conditions

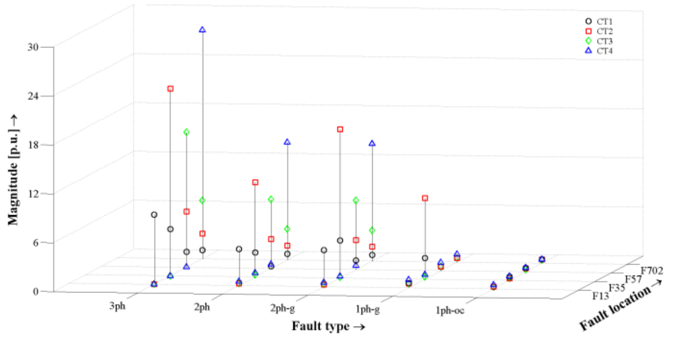

Fig. 6a: Positive-sequence set during abnormal conditions

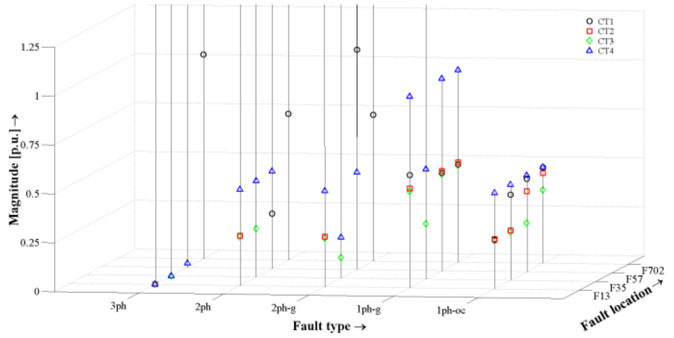

Fig. 7a: Positive-sequence set during abnormal conditions (magnified)

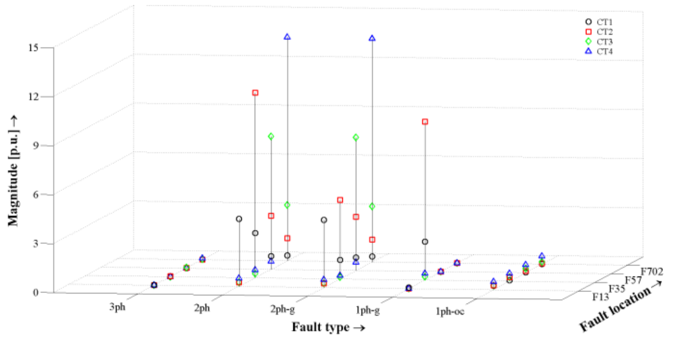

Fig 6b: Negative-sequence set in abnormal conditions

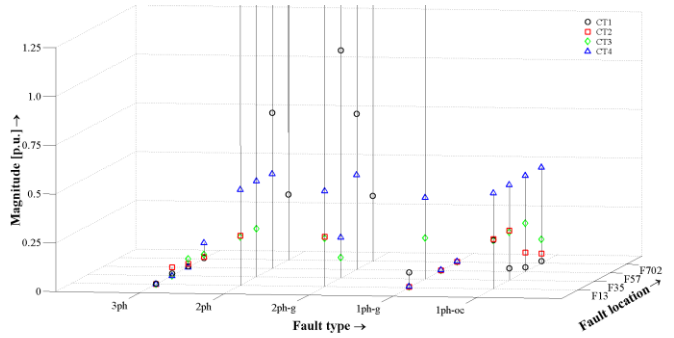

Fig 7b: Negative-sequence set in abnormal conditions (magnified)

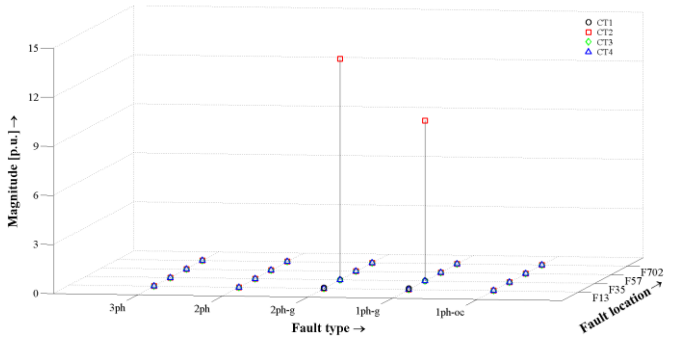

Fig. 6c: Zero-sequence set in abnormal conditions

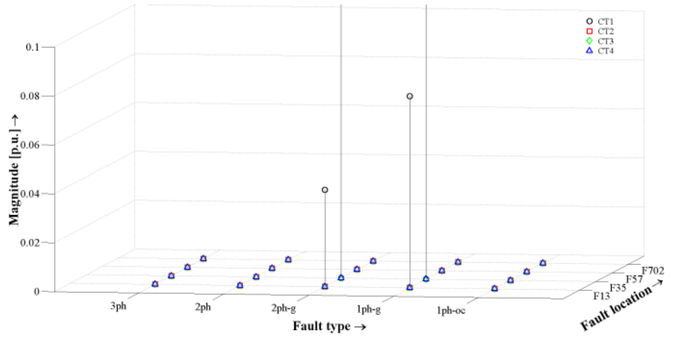

Fig. 7c: Zero-sequence set in abnormal conditions (magnified)

For a better observation of the low currents, Fig. 7 presents a magnified version of Fig. 6, with focus on the sequence sets with a magnitude bellow the defined pickup current. It is clear that a current corresponding to the magnitudes indicated in Fig. 7 are unlikely to trip the conventional overcurrent relay that is fed by the indicated CT, as the fault is outside the relay's reach. Such behavior is acceptable if that fault is outside the primary zone of protection and other relays are able to offer the backup protection. However, it is not the case of the 1-phase open circuit conditions and of some ground faults. Moreover, the 2-phase and 2-phase to ground faults do not produce high currents for the CTs that should be part of the backup protection for the considered feeder. Precisely in these particular conditions, examination of the symmetrical components gives information that could indicate a fault that is invisible to a conventional overcurrent relay. For example, the interrupted phase conductor produces similar magnitudes for the positive and negative-sequence sets in the CTs of the outgoing feeder in all situations, as depicted in Fig. 7. Also, the faults involving 2 phases are indicated by similar values of the positive and negative-sequence currents in some CTs, while the 1-phase to ground fault in location F13 is indicated by the presence of all sequence-sets.

The discussion is concluded by stating that the single phase fault cannot be detected if it occurs in a part of the network that is ungrounded (locations F57 and F702), as the previous pictures illustrate. Also, the magnitudes of the zero and negative-sequence currents are less than *0.05 p.u.* of the rated current if the single phase fault occurs in a system that is grounded through a high resistance (location F13). Such values may be difficult to detect, so other types of protection, as the directional overcurrent relay [2] are needed in this case.

4.2 Symmetrical components for faults at load location

The positive and negative-sequence sets of the currents seen by the CTs of the network in configuration 1 for different faults that are located at the loads terminals (F10, F30, F50 and F701) are shown in Fig. 8. For each CT, the magnitudes are expressed in per units of the rated positive-sequence set for that CT. The zero-sequence sets are not presented because all these currents are zero for the considered locations of the faults. Similar to the previous locations, the 3-phase fault is indicated only by the positive-sequence currents, but in this case none of the CTs are able to detect it at location F10 because the fault current is not passing through any CT.

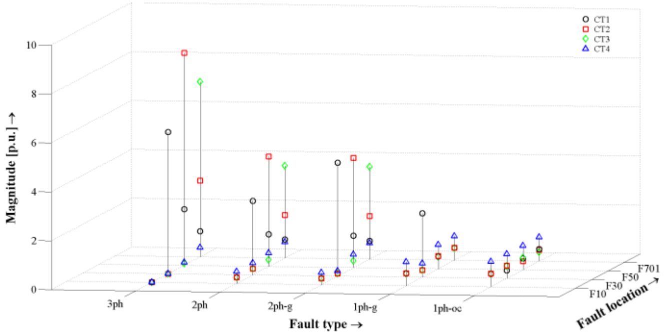

Fig. 8a: Positive-sequence set during abnormal conditions (load location)

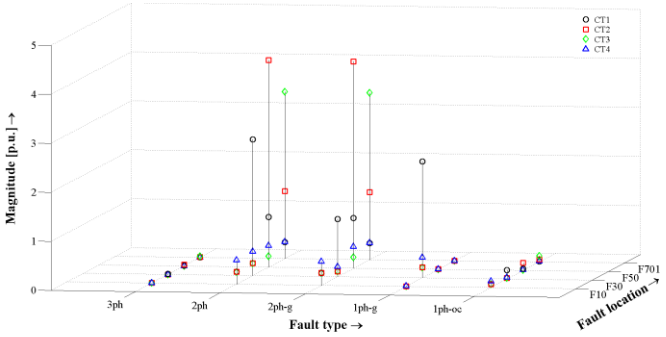

Fig 8b: Negative-sequence set in abnormal conditions (load location)

Interruption of the phase conductor does not produce a great effect on the currents measured by the indicated CTs. The positive-sequence sets are around the rated value, while the negative-sequence sets are low and cannot be used to detect the interrupted phase because the same negative-sequence currents could be produced by the load unbalance. Moreover, out of the single phase faults, only the one located in the ungrounded part of the network (F30) can be identified using the symmetrical components as it produces almost equal positive and the negative-sequence sets. Examination of Fig. 8 indicates that the faults involving 2 phases produce high amounts of negative-sequence currents for some CTs or similar values to the positive-sequence sets for the remaining CTs. For example, the faults involving 2 phases at location F10 are characterized by equal sequence sets (positive and negative), while for the other locations at least one CT current exceeds the pickup current of a typical overcurrent relay. As result, the 2-phase and the 2-phase to ground faults occurring at the load terminals could be detected by the CTs placed along the radial feeder of the maritime power system.

5 Conclusion

Analysis of the fault currents using method of symmetrical components for the considered network, leads to the general conclusion that the conventional overcurrent protection could be improved in some conditions. Symmetrical components of the fault current provide additional information regarding the abnormal condition that is found in the network. In the case of the analyzed maritime power system, using only the CTs corresponding to the time-inverse overcurrent relays, most the electric faults located along the feeder were detected. More than that, the reach of the overcurrent elements can be extended in some cases (for example, the faults involving 2 phases at locations F701 and F702 for CT1) if the negative currents are considered alongside the positive-sequence set. It was also emphasized the need of adaptive protection for a reconfigurable power system, as even the currents in normal conditions are dependent on network status. Moreover, the analysis performed in this paper showed that for several abnormal conditions, the magnitude of the currents measured by some CTs is in the same range as the rated current. As result, any protection system that is based on the method of symmetrical components needs to be adaptive as well for the reconfigurable networks in the maritime sector.

The results of this paper show that a relay that compares the symmetrical components of the current might offer improved results over the conventional overcurrent relays. However, future work is needed in order to prove the effectiveness of the method in other situations, as the other configurations of the network or different maritime applications.

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