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Protection of MVDC Shipboard Power System using Rogowski Coil

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Abstract—One of the major challenges faced in the design of DC shipboard power systems (SPS) is the provision of effective DC protection. The selection of the current sensors plays an important role in the detection of fault current in DC systems. The Rogowski coil has emerged as a popular choice of current sensor for use in DC SPS protection system primarily because of its fast response and non-saturable property. This paper presents the modelling and operation of the Rogowski coil and its integration into protection algorithms to achieve effective protection. With this method, the transient conditions experienced during faults can be effectively identified and differentiated.

Index Terms—DC Shipboard Power system, DC Faults, Directional Protection, Rogowski Coil, Short-Time Fourier Transform

I. INTRODUCTION

One of the major challenges faced in the design of DC shipboard power systems (SPS) is provision of effective protection system [1]–[3]. The fast rising fault current and lack of current zero in DC SPS aggravates the problem. AC protection philosophy cannot be directly applied to the DC SPS [4] but it might be used as a base model to define the approach to realise DC protection. Generally the protection system consists of current/voltage sensors, fault detection algorithms (programmed as numerical relays) and fault isolating device (circuit breakers). The current sensor is one of the crucial elements of the protection system as most algorithms are based on detecting the rapidly changing current profile during faults. However, the methods for fault detection in the existing literature assume that suitable current sensors exist and these provide the relay with high fidelity measurements [5]–[7]. Apart from the high fidelity current sensors, another important challenge is the development of the fast fault detection algorithm.

The generation system of typical DC SPS comprises diesel generators interfaced directly with converter/rectifier systems. The two level voltage source converter (2L-VSC) is widely used [8]–[9]. A typical DC fault current in DC SPS is the sum of the capacitive discharge current (contributed by the DC-link capacitors) followed by the fault current supplied by the interfaced generators [10]. This fault current supplied by the interfaced generator is primarily responsible for to damage the freewheeling diodes of the interfaced converters. The

withstand capacity of the freewheeling diodes is determined by its rated I^2t capacity as determined by its manufacturer [11]. From Figure 1, it can be observed that the I^2t limit of the freewheeling diode reaches within very short time (5 ms). This short duration of time places challenging performance requirements upon the fault detection algorithms.

Figure 1. Typical DC fault current and change in I^2t of the freewheeling diodes.

This paper is divided into six sections. Section II deals with the current transducers used in the DC SPS. Modelling and operation of Rogowski coil is covered in this section. Fault studies in DC systems and a representative DC SPS is discussed in Section III and Section IV respectively. The protection systems implementing Rogowski Coil is covered in Section V which is followed by conclusions in Section VI.

II. CURRENT TRANSDUCER FOR DC SPS

The current transducer (CT) is an important component of DC SPS and is required to measure the fault current for fault detection. There are a variety of current sensors available for detection of fault current. These include shunt resistors, current transformers, Hall-effect sensors and Rogowski coils (RC). The RC is primarily used to measure high frequency alternating current and pulsed loads. It is a low cost, linear device which does not saturate at higher values of currents as shown in Figure 2(a). Moreover, its minimal power consumption and very low output variation with temperature makes it compelling choice over other CTs. RC is generally used to

Figure 2. (a) Characteristic of difference current sensing devices, (b) output of RC during the fault condition, (c) RC output for different types of faults and (d) lumped model of RC.

measure the fast changing current profile and hence is suitable to detect DC faults as depicted in Figure 2(b). Figure 2(c) compares the output of the RC for different fault resistances and load changes. It can be seen that the output of RC changes rapidly with change in fault current as compared to the load change. In this paper lumped resistor model of RC is used for the modelling purpose [12] (Figure 2(d)). The number of turns within an RC is an important parameter, increasing in number of turns increases the sensitivity. The output of the RC depends on the mutual inductance between the current carrying conductor and the RC. Since RC is typically air core, one of the prime factors in deciding the output is the number of turns (N) [12]–[13]. The electrical parameters of the coil depend upon the geometry of the design. Since the coil resistance is negligible, as compared to the terminating resistance, the transfer function of the lumped model of the RC can be given by Eq. 1 [13], [14]:

$$H(s) = \frac{V(s)}{I(s)} = \frac{s.M}{L_l C_l s^2 + (R_l C_l + \frac{L_l}{Z}).s + 1} \quad (1)$$

where R_l is the resistance, L_l is the inductance, C_l is the capacitance, M is the mutual inductance of RC and Z is the terminating resistance. These parameters can be calculated from Eq. 2,3 [13], [14]:

$$R_l = \rho_c \frac{l_w}{\pi d^2}, \quad L_l = \frac{\mu_o N^2 d_{rc}}{2\pi} \ln \frac{b}{a}, \quad C_l = \frac{4\pi^2 \epsilon_0 (b+a)}{\log(\frac{b+a}{b-a})}, \quad (2)$$

$$M_l = \mu_o N \frac{r_m - \sqrt{r_m^2 - r_{rc}^2}}{4\pi}, \quad R_d = Z = \frac{1}{2\zeta} \sqrt{\frac{L_l}{C_l}}, \quad (3)$$

where ρ_c is the electrical resistivity of the coil wire, μ_o is the permittivity of free space, l_w is the length of coil wire, d is the radius of the wire, d_{rc} is the diameter of each loop in the RC, r_{rc} is the radius of each loop in the RC, r_m is the mean radius of the RC, N is the number of turns and a, b are the internal and external radius of the RC. The terminating resistor is a determining factor of the coil output quality. $\zeta = 1$ is used to calculate the terminating resistor to ensure critically damped condition. Table I is prepared using Eq. (2, 3) which comprises of the parameters of the RC for different number of turns. However, the major drawback of the RC is the need of an integrator to translate the output voltage of the coil into

a current waveform. The integrator further needs a separate power source for its operation.

III. FAULT STUDIES FOR DC SPS

During the fault, the DC-link capacitor is the first element to discharge to the fault point [2]–[3], [15] and the direction of the capacitive discharge is dependent on the fault location [2]–[3], [15]. To understand the capacitive current contribution on the fault current, calculations are carried out on a representative system (Figure 3(a)) comprising of 1x2048 kVA generator fed AFE rectifier and 1x883 kW VSI fed propulsion motor. Figure 3(a) also describes the equivalent circuit for the capacitive current discharge during pole-pole fault occurring at 1 s with fault resistance R_f . However to account for the worst case scenario, bolted short circuit ($R_f = 0 \Omega$) is considered in the calculation as the severity of the fault current magnitude quite high. The fault current ($I_1(s)$ & $I_2(s)$) calculations for bolted fault ($R_f = 0\Omega$) can be calculated from Eq. 4(a, b).

$$\frac{V_o}{s} + L_{t1} I(0) = \left(R_{t1} + sL_{t1} + \frac{1}{sC_1} \right) I_1(s) - I_2(s) R_f \quad (4a)$$

$$\frac{V_o}{s} + L_{t2} I(0) = -I_1(s) R_f + \left(R_{t2} + sL_{t2} + \frac{1}{sC_2} \right) I_2(s) \quad (4b)$$

where $R_{t1} = 2r_{c1} + 2R_1$, $L_{t1} = 2L_1$, $R_{t2} = 2r_{c2} + 2R_2$ and $L_{t2} = 2L_2$ as shown in Figure 3(b). The fault current and the output of the RC for different cases of Table I is shown in Figure 3(c) and Figure 3(d). It can be seen that the DC-link capacitor of the rectifier and inverter discharges at the fault point as expected. The direction of propulsion load fault current $I_2(s)$ changes to negative which forms the basis of directional protection discussed in the next section. The fault currents from the generator $I_1(s)$ and that from the motor $I_2(s)$ may be overdamped, underdamped or critically damped which depending on the circuit parameters (R, L, C).

IV. TARGET DC SHIPBOARD POWER SYSTEM

The representative DC SPS for fault study is shown in Figure 4. The generation source comprise of synchronous generator interfaced with the 2L-VSC. The loads comprise of inverter fed propulsion loads, inverter fed houseloads and pulsed loads. The current is sensed with the help of RC. The IDs indicated in the Figure 4 are the ‘intelligent devices’ which

TABLE I
LUMPED MODEL PARAMETERS

Case	Number of Turns (N)	Length of Coil (l) (m)	Radius of the Coil (r) (m)	Diameter of loop each (h) (m)	Inner Diameter (d) (m)	Outer Diameter (D) (m)	$L_1(\mu H)$	C_1 (pF)	R_d (Ω)	M_1 (μH)
1	120	0.5	0.079	0.002	0.078	0.080	5.003	29	49	0.874
2	150	0.5	0.079	0.002	0.078	0.080	7.817	29	49	1.093
3	180	0.5	0.079	0.002	0.078	0.080	11.257	29	49	1.312
4	210	0.5	0.079	0.002	0.078	0.080	15.322	29	49	1.530
5	240	0.5	0.079	0.002	0.078	0.080	20.01	29	49	1.749

Figure 3. (a) Representative system comprising of one generator and one propulsion load for fault calculation, (b) the equivalent circuit depicting the capacitor discharge during the fault, (c) the current contribution by the generator ($I_1(s)$) and (d) the current contribution by the propulsion load ($I_2(s)$).

comprises of relays for fault detection algorithm processing and circuit breakers for fault isolation. The schematic of ID is shown in Figure 5 [3]. The pulsed load in Figure 4 are used in the emerging naval ships particularly for electromagnetic guns [16]. The circuit diagram of the pulsed load is shown in Figure 6(a). In this paper the ON time of the pulsed load is set to 20ms. The time-current characteristic of the pulsed load is shown in Figure 6(b).

Figure 6. (a) SLD of the pulsed load and (b) time-current characteristic of the pulsed load.

Figure 4. SLD of the representative DC SPS.

Figure 5. Typical arrangement of intelligent device (ID).

V. PROTECTION OF DC SHIPBOARD POWER SYSTEM

In the previous sections, it is indicated that fault identification and isolation processes must be completed prior to the onset of damage to the freewheeling diodes of the interfaced converter. This requirement implies that the protection system should operate within first few milli-seconds (say 5 ms) which demands stringent operation of the current sensors as well as fast operation of the protection algorithms. RC is chosen for its high bandwidth and simple operation. The next hurdle is in realising the fast fault detection algorithm. For faster operation of the protection algorithms, unit protection must be employed utilising the local parameters such as line current and line voltage.

A. Directional Protection

Directional based protection system with RC as current sensor is used for different fault and transient conditions. As discussed in Section III, the fault current direction is dependent on the fault location. From Figure 3 it can be realised that

Figure 7. (a) Fault current direction during fault at generator F1, (b) output of Rogowski coil (RC1) during various fault resistances and sudden load throw-off and (c) operation of ID1 for fault F1 based on RC1 output.

Figure 8. (a) Fault current direction during fault at propulsion system F2, (b) output of Rogowski coil (RC4) during various fault resistances and sudden propulsion motor start and (c) operation of ID4 for fault F4 based on RC4 output.

Figure 9. (a) Current direction during fault at pulsed load and pulsed load operation, (b) output of Rogowski coil (RC7) during pulsed load of various magnitudes and (c) output of Rogowski coil (RC7) for different fault resistance and pulsed load.

for fault F , the current direction of propulsion load changes from its normal direction. However, the current direction may also change for other reasons such as load switching and regeneration of propulsion load. The line voltage always reduces in case of fault. Thus apart from the change in current direction, the line voltage should also be monitored to get confirmed results. Intelligent device (ID) which is shown in Figure 5 is widely used to implement the protection algorithm.

In this paper direction of current is set to be positive when current flows from the generator to load side and is set to be negative when current flows from load to generation side.

1) Faults at Generator Side: In Figure 7(a), for fault $F1$ at Gen-1 rectifier output, all the generators and active loads will contribute to the fault current. The output of the RC2 is positive while all other RCs show negative output thus indicating that the fault has occurred at $F1$. Hence, the direction

of current through RC1 is the indication whether the fault has occurred or not. Since RC measures the rate of change of current, a threshold must be set to operate the protection algorithm as shown in Figure 7(b). This threshold depends on the construction of the RC as explained in Section II. RC is modelled according to the Case 5 lumped parameter (Table I) and the threshold setting for this RC is chosen to be -25V.

2) *Faults at Propulsion Motor Side:* During the fault at propulsion motor side (F_2) in Figure 8(a), the output of the RC4 will be very high hence the ID4 will be tripped in overcurrent protection. The setting of overcurrent threshold is of prime importance as it should not interfere with the transient currents of the propulsion system (Figure 8(b)). The transient current from the propulsion system result from sudden loading and de-loading of the propulsion system which is the result of the in-and-out-of water effects [17]. The transition from no-load to full-load might interfere with the protection settings. For this paper, the setting of RC4 is set at 25V.

3) *Operation of Pulsed Load:* The pulsed load operates for very small duration (20ms) as explained in Section IV [16]. Pulsed load of different magnitudes are studied when combined with the RC. Operation of pulsed load would result in overcurrent and the protection system should be able to distinguish the pulsed load and the faults. With the RC threshold setting at $\pm 25V$ as explained in earlier sections, pulsed load is suitably distinguished as depicted in Figure 9.

B. Protection implementing Short-Time Fourier Transform

Apart from the change in direction of the current, the rate of rise of current during faults is another important parameter for fault identification. From Figure 2(c) it can be seen that the rate of rise of fault current is dependent on the type of faults and loading condition. The current may rise rapidly for bolted short circuit but the rate of rise would be less than the pulsed load or other transient loads. The fast fourier transform (FFT) analysis for a current signal for bolted short circuit and pulsed load on base frequency of 250 Hz is shown in Figure 10. It shows the magnitude of the frequency components relative to the fundamental frequency (250 Hz). For the short circuit fault, the fault current comprise of high frequency components which can be seen by higher magnitude of 250 Hz component when compared with the DC (0 Hz) component. The pulsed load also comprise of high frequency components but the magnitude is lower as compared with that of short circuit fault currents. Thus this analysis and detection of high frequency components in current can be used to segregate the fault from the non-faulty condition. The detection of the presence of high frequency components can be done with the help of short-time fourier transform (STFT) which is shown in Figure 11 [18]–[20]. The STFT algorithm and its application is discussed in subsequent sections.

1) *STFT Algorithm:* STFT algorithm computes Fourier Transform of the fault current signal over a period determined by the window function $w(n)$. This algorithm can be given by

Figure 10. FFT of the current waveform for (a) bolted short circuit, (b) pulsed load.

Figure 11. Schematic of short-time fourier transform.

Eq. 5.

$$STFT(n, k) = \sum_{i=n}^k x(n)w(n - mH)e^{-j\frac{2\pi}{N}kn} \quad (5)$$

where, k = frequency index, N = FFT size (number of samples), $x(n)$ = input signal, $w(n)$ = window function, m = position of window and H = hop size between successive windows. Hamming type window function is used to compute the STFT and the fault current signal is sampled at 5 kHz which is in-line with the sampling frequency of modern protection relays. The windows are overlapped by 50% which is decided by the hop size between the successive windows. Overlapping is done to increase the time resolution without affecting the frequency resolution.

2) Application of STFT Algorithm:

- 1) For the fault F_1 at the Gen-1 terminal, RC1 senses huge current as compared to RC2. It is expected that the fault current through RC1 hence ID1 will comprise of high frequency components as compared to RC2 (ID2). STFT analysis in Figure 12 shows that Gen-1 current comprises of high frequency components as compared to Gen-2 current. This can be used as another indication apart from directional feature.
- 2) For the faults at bus-bar, it is expected that the Gen-1 and Gen-2 would contribute equal amount of fault current which can be confirmed by the STFT results in Figure 13. The Gen-1 and Gen-2 current have similar

Figure 12. (a) Comparison of the RC output and fault current for bolted short circuit, (b) RC output for different fault and loading conditions.

rate of rise of current hence have similar frequency spectrum.

Figure 13. (a) Comparison of the RC output and fault current for bolted short circuit, (b) RC output for different fault and loading conditions.

C. Fault Isolating Device

For DC SPS having such stringent requirements, the fault isolating device must be able to isolate the faulty section as fast as possible. Fuses are the simplest fault isolating device which operates on the thermal characteristics of the fault current [21]. However, fuses are single shot devices and the co-ordination of protection is difficult. The solid-state circuit breaker (SSCB) is able to extinguish the fault current in several micro-seconds and are able to limit the fault energy [22]. Apart from SSCB, the existing AC circuit breaker (ACCB) can be modified using LC oscillator circuit [23]. DC-DC converters with bi-directional power control can also be used for fault isolation [24]. Apart from the fast acting protection algorithms, the fault isolating device should be able to isolate the faulty system within 5 ms as described in Section I.

VI. CONCLUSION

This paper studies the implementation of Rogowski coil (RC) for the protection of DC SPS. The modelling of the RC was carried out to detect the fast changing current during faults in DC SPS. The sensitivity of the RC can be increased by increasing the number of turns which increases the mutual inductance. The RC is integrated with the directional protection algorithm which can accurately distinguish between transient and fault conditions. However, it is difficult to distinguish transients like propulsion system loading and de-loading due to very low rate of change of current as compared to the fault currents. Short-time Fourier Transform is also discussed which

can also be used in combination with the directional protection for added redundancy.

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