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Distributed Insulation Monitoring Strategy (DIMS) for High Stray Capacitance Systems

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Abstract. Climate change is a global phenomenon which is becoming increasingly concerning. International efforts, such as the Paris Agreement [1] lead to transport electrification initiatives. HYPOBATT [2], in marine sector, aims for the charger that will enable a full electric vessel to be a reality. These systems have great amounts of energy storage. Together with electric machinery, EMI filters and distribution grids usually can sum up to some mF capacitance to earth, becoming a problem when detecting faults to ground, and therefore, a safety issue.
To detect earthing faults insulation monitoring devices (IMD) are used, but as of Jan. 2024, the commercial IMDs available are not able to make a good measurement at stray capacitances (C_S) above 3000µF [3], and all the devices in the mF range have response times of >100s.
A new Distributed Insulation Monitoring Strategy (DIMS) approach is proposed in this paper, with simulation results, to make a faster and more reliable measurement of earthing faults in isolated terra (IT) systems with stray capacitances in the range of the hundreds of µF. The impedance to ground is measured in isolated parts of the whole system and then a higher-level logic is implemented to compute a total safety status.

Key words. Stray capacitance, modular insulation monitoring, IT systems, marine transport electrification, energy storage system.

1. Introduction

To reduce CO2 emissions and limit global warming due to greenhouse effect, emissions in marine transport need to be reduced. To do so, initiatives like HYPOBATT [2], aim to develop the tools needed for fully electric ships to become a reality.

Hybrid and full electric ships have great energy storage systems (ESS) which typically have stray capacitances of 1nF/kWh. As shown in

Table 1, many full electric vessels have stray capacitances way above the limits of the modern IMD device capacities and therefore, this issue needs to be tackled to ensure that safety within the vessel is kept and that the charging process times do not interfere with the mooring, loading and similar times due to the long insulation checks.

Table 1. – Reference stray capacitance due to ESS

Manufacturer/model	ESS	Rough C_S
Ærø / E-Ferry	4.3MWh	>4.3µF
Yara / Birkeland	7MWh	>7µF
Wärtsilä / Buquebús ferry[1]	40MWh	>40µF
COSCO / N997	50MWh	>50µF

Another typical source of stray inductance is electrical machinery, being normal to have around 100nF/MW of machine power.
In addition to these, EMI filtering capacitors are usually placed to ground, and they should be much larger ($C_F > 3 \cdot C_S$) than the system stray capacitances to effectively suppress CM supra-harmonic noise in the frequency bandwidth 2-150kHz [4].

Current IMD implemented techniques are usually based in DC voltage injection and resultant current measurement. This current is a result of a variety of the system characteristics (see Figure 1). The capacitance and absorption currents are transient components and tend to zero with time. The leakage current, on the other hand, is stable with time and gives the best image of the insulation.

[1] Expected to operate by 2025.

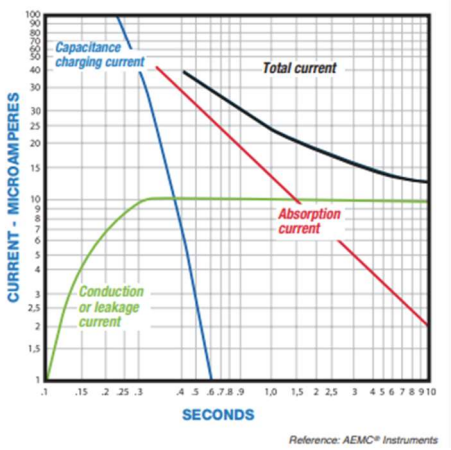

Figure 1. Current decomposition during insulation measurement [5]

Due to this, and to have a proper measurement, many methods can be used:

- Short-time or spot-reading measurement.
- Polarization Index (PI).
- Dielectric Absorption Ratio (DAR).
- Step voltage test.
- Dielectric Discharge (DD).

Some manufacturers do have proprietary methods too, like AMP method [6] by *Bender*.

In any case, all these methods depend on the device current capabilities and systems capacitance and insulator characteristics to provide a proper measurement, due to the transient components mentioned above.
Due to this, and to reduce the effect of the system characteristics, a new approach is needed to provide faster reliable measurements.

2. Distributed Insulation Monitoring Strategy

In an IT circuit the conductors are floating with respect to the earth potential (PE), so it is mandatory to check the insulation level. This is done usually by measuring the impedance of the different circuit potentials to PE and it is known as common-mode (CM) impedance.

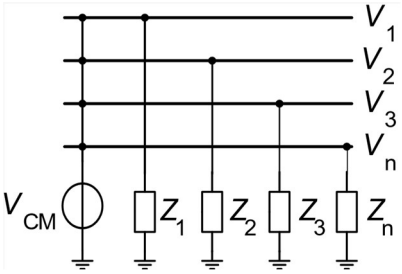

Figure 2. Potentials to earth impedances

To do so, it is necessary to apply a CM voltage to the potentials checked (see Figure 2) and measuring the CM current out of the CM voltage source, a total impedance can be computed. This total impedance is a sum of all the parallel impedances to PE potential in the circuit, following (1).

$$\frac{1}{Z_T} = \sum_{n=1}^{N} \frac{1}{Z_n} \qquad (1)$$

In the case of an AC distribution system, the measured potentials would be the active lines (usually up to three) plus the neutral line. On the other hand, in a DC distribution system, the measured potentials would be the poles, typically DC+ and DC-. The impedance of such lines can be either parasitic or through a dedicated device, like the so-called Y capacitors, for example.

A. System earthing in ships

Most ships have IT electrical circuitry aboard. This is mainly due to the hull being metallic and accessible, among other reasons. Usually, PE potential in the ship is connected to the hull and exposed conductive parts connected to it. In this manner, if a single fault occurs, because the system is IT, the hull is still touch-safe [7].
Regarding the shore side, once the vessel is moored, the PE potential ashore is connected to the hull, see Figure 3.

B. Charging process and continuity of service

Ships like ferries have schedules to follow so timing is important for the continuity of service. If the safety check takes too long valuable charging time is lost and the ship might not have the energy to fulfil the expected route.

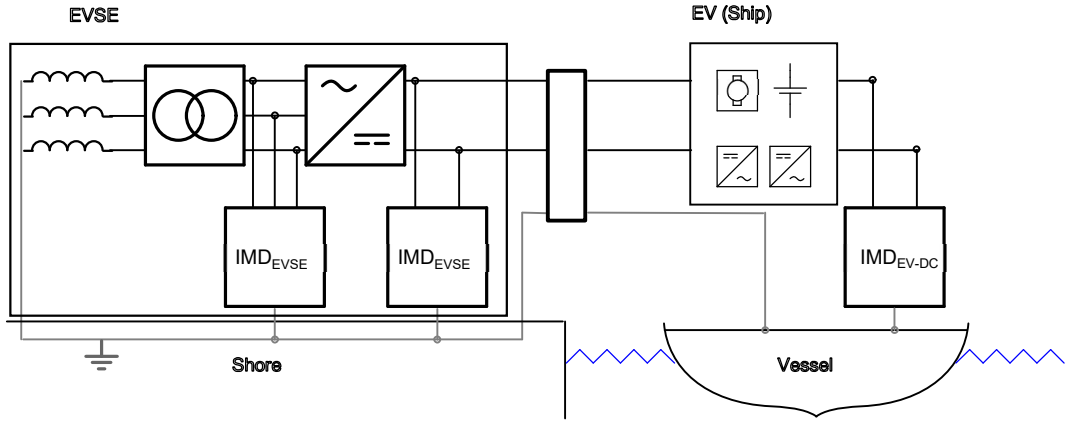

Figure 3. Main connection scheme

Table 2. Response times of commercial IMDs

Device	R_E[kΩ]	C_S[µF]	t_{RES}[s]
Bender isoPV1685RTU [8]	50	2000	700
		500	300
	0.4	2000	80
		500	35
ABB CM-IWM.11 [9]	2000	3000	6500
		50	160
	100	3000	550
	1	3000	140
		50	18

It is also important in terms of safety, because when moored, as shown in Figure 3, the hull is earthed and a fault that was not critical previously becomes dangerous when the fault is connected to earth.
Therefore, response time is critical for both continuity of service and passenger safety.
Table 2 shows the best- and worst-case response times of the two commercial IMDs with greatest stray capacitance capabilities. Best case (shortest measure time) would be least stray capacitance (C_S) and faulty insulation resistance (R_E), whilst worst case (longest measure time) is greatest capacitance and well isolated installation. Looking at the times, the only possibility to detect a fault in few seconds would take to make measurements in circuits with stray inductances below 50µF.

C. Proposed DIMS

As mentioned in the introduction, capacitance to ground in electric ships can sum up to some hundreds of µF, and commercial IMD devices have response times of several tens of seconds and that is not acceptable in charging applications that require keeping up to a planned schedule.

One possibility is to take advantage of the switching gear both in the ship side and shore side and perform insulation checks disconnecting circuit parts to limit stray inductances below some tens of µF before connecting ship and shore. This way, system is split into smaller monitoring cells and check can be performed quicker and in a safe manner.

- Cell-1: Onshore charger.
- Cell-2: Battery pack 1.
- Cell-n: Element n.

Nonetheless, and specially on the ship side, disconnecting equipment is tricky, in the sense that continuity of service must be ensured, and therefore strategies must be implemented to perform checks following a sequence that allows both insulation checks to be performed and minimum operation requirements to be met.
Assuming continuity of operation can be assured, on the vessel side every battery pack should have circuit breakers to allow disconnection in case of failure and modular operation and by means of these devices, battery packs could have their isolation tested on their own before connecting to the shore. Traction chains could also be disconnected by means of contactors and/or breakers, reducing the isolation measuring cell size. In the same manner, if any auxiliary converter or other equipment was connected to the same DC bus, it should be disconnected from it, also by means of a breaker or contactor.
On the charger side, pre-charge contactors and/or AC breakers would disconnect the converter from the grid and therefore, before connecting to the battery system, an insulation check can be performed to the converter itself. If for EMC purposes on charger side a larger than 5 µF overall Cy is needed, it can also be divided into multiple cells.
Measurement would be done to every single cell depicted in Figure 4, while the vessel is not connected to shore. As a result, this decouples charger isolation issues with respect to vessel issues. A full insulation check should not take longer than a couple of minutes, therefore in case of periodical checking, it should not reduce effective charging time by a significant amount of time (few minutes checking vs few hours charging). Two way 'handshake' can be implemented to allow charging or not by checking onshore and vessel insulation statuses increasing security. Vessel insulation check should be managed by onboard BMS and/or main control computer and communicated to the shore. Full flow chart is proposed in Figure 5.

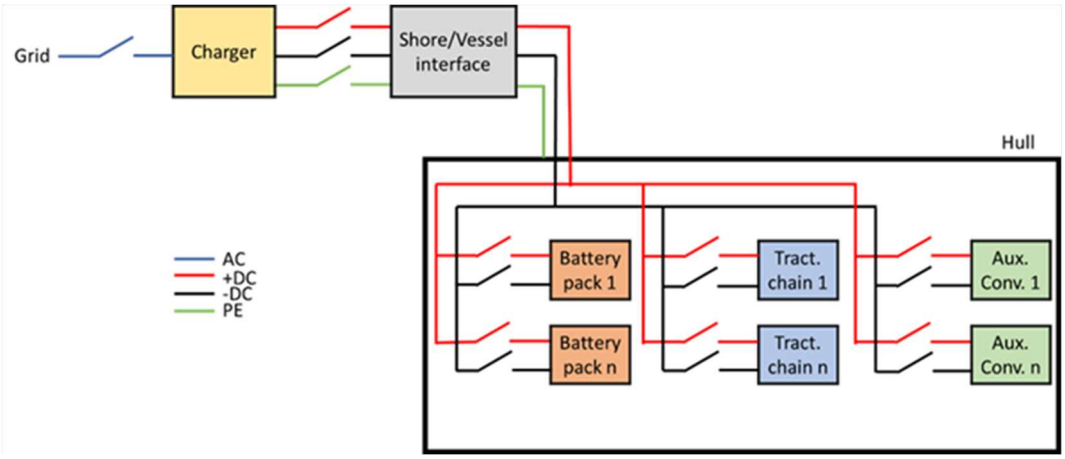

Figure 4. Cell disconnection concept diagram

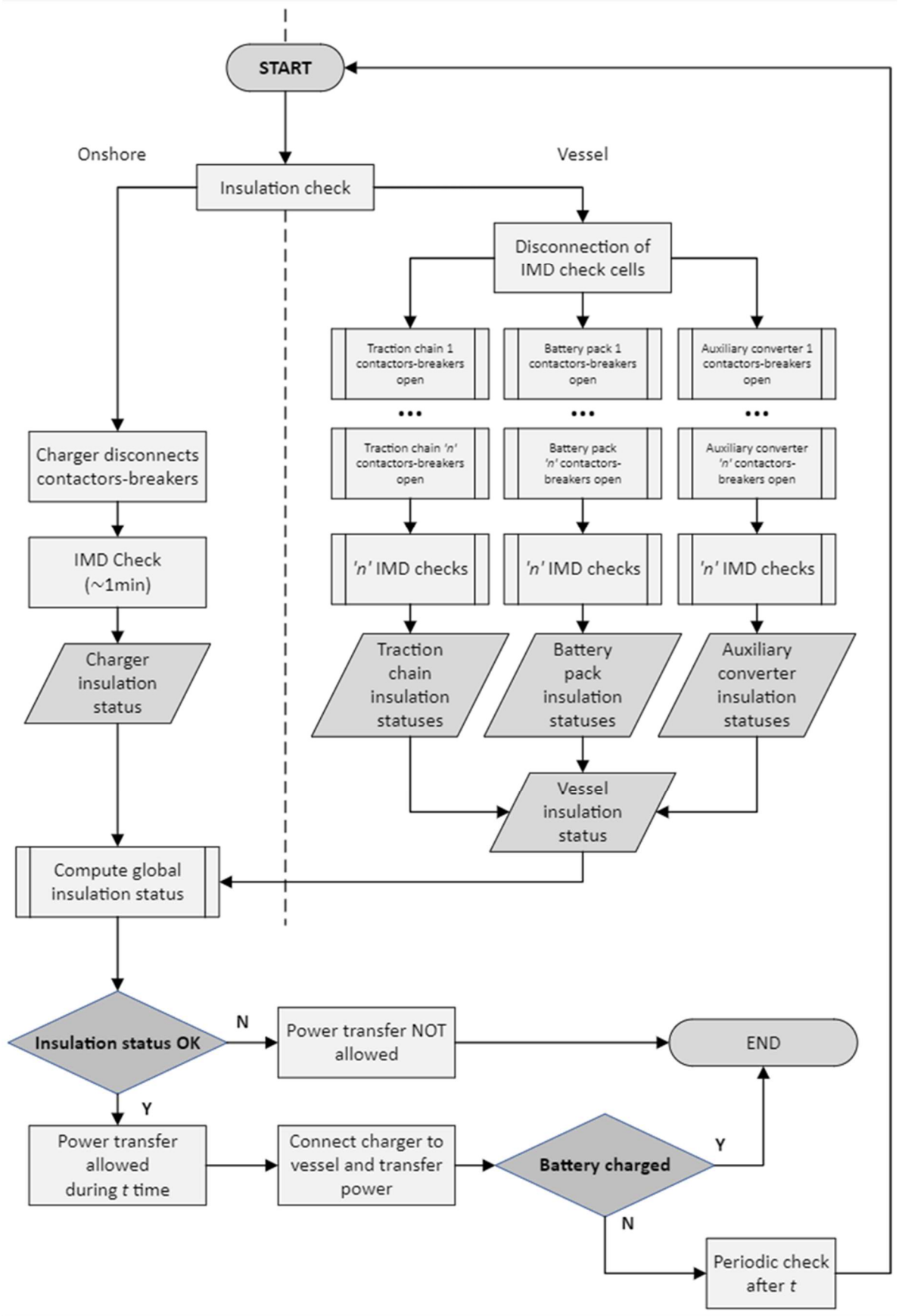

Figure 5. Proposed insulation check algorithm

3. Simulation results

To quantize the time improvement of dividing the stray capacitance two approaches have will be presented. Firstly, a reference design by TI, TIDA-010232 [10], was implemented in *PLECS*® and simulated under ideal conditions and therefore, a use case example has been analysed with the two commercial models listed in Table 2

A. PLECS simulation

The reference design by Texas Instruments allows insulation resistance measurement by connecting a resistor chain to the system lines. It is only valid for DC lines.
This design needs a sampling time long enough to consider the stray capacitance, so the measurement precision is enough. This is because measurement is done sequentially in the different lines and all measurements are considered in the total calculation.

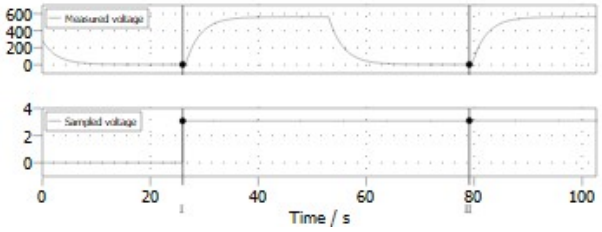

Figure 6. Simulation IMD sampling example

This IMD was implemented in a model which is shown in Figure 7 as a 1 cell version (whole system) and then divided to 2 and 3 cell systems. Being this so, simulations were carried out to compute an *'Insulation status'* bit which goes Boolean 1 when measured resistance is above 100kΩ and Boolean 0 when below 10kΩ, in a hysteretic manner. Simulated stray capacitance values have been 50µF, 100µF, 200µF and 500µF, while simulated insulation resistance was 10MΩ. Each capacitance value was tested in full and divided in 2 and 3 equally valued IMD check cells.

Table 3. Response times in different simulation conditions

C_e[µF]		50	100	200	500
t_{Res}[s]	1 cell	159.10	318.21	636.42	1591.06
	2 cells	79.55	159.10	318.21	795.53
	3 cells	53.03	106.07	212.14	530.35

As shown in Table 3, response time in these simulations is linearly proportional to the stray capacitance. This is because no current limitation was implemented in the measurement. In commercial devices different strategies are considered when it comes to current and voltages levels, this is why a practical use case will be studied using available device information.

B. Commercial device analysis

Commercial devices like the ones listed in Table 2, typically have configurable stray inductance parameters, so system can adjust measurement times, in a similar way to that carried out with the Texas Instrument reference design. In the case of the *'ABB SM-IWM.11'* if maximum insulation resistance is taken (>2MΩ), reducing the stray capacitance from 100µF (as a reference value of the greatest expected order in actual or near future systems) to 50µF reduces from 370s to 179s and to 102s if reduced to 33µs. This is aligned with the simulation results, as it is quite proportional to the capacitance. This relationship is different at lower RC relationships, as device current can keep response times more constant (see measuring times in [9]). For higher RC values current is limited due to safety reasons [11], that's why response time is affected by RC time response.
Regarding the *'isoPV1685RTU'* model from *'Bender'*, interpolation in the response time for insulation measurement chart [8] happens to be very inaccurate due to the lack of information, therefore, another commercial IMD from bender has been analysed, 'iso685' family [12]. When observing the high capacitance profile of the device, at maximum insulation resistance (>2MΩ), reducing the capacitance from 150µF (no 100µF curve available in the chart) to 50µF, response time reduces from 350s to 120s and further reduces to 70s if reduced to 20µF. Relationship remains similar to *'ABB'* device and simulations, and it is expected to be coherent with other *'Bender'* products.

4. Conclusion

In this paper a new DIMS has been proposed and validated in simulation, demonstrating an improvement for specific applications where the capacity is large and commercial products are limited. Stray capacitance clearly affects the time requirements in IMD schemes. DIMS strategy presented in this paper has demonstrated to reduce the effective stray capacitance in the measuring circuit and, thus, reduces the time needed to provide a safety check proportionally.
In applications with tight time and safety constraints this novel strategy can become crucial.
The most limiting aspect would be the need of physically switching the architecture, and this would require further analysis to determine the feasibility of the DIMS in each singular application.

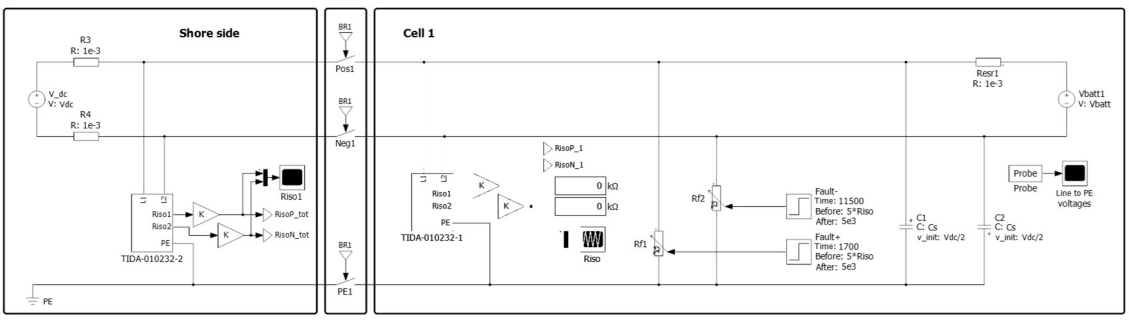

Figure 7. PLECS simulation model, single cell version

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