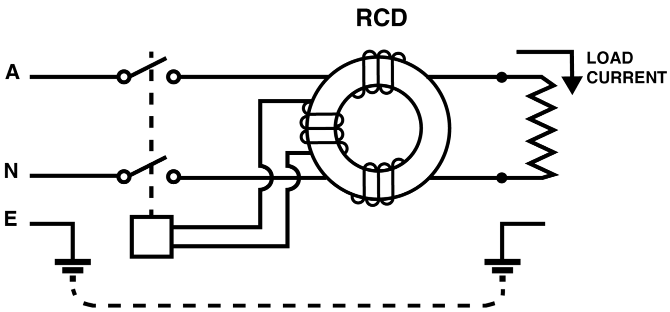
RCD nuisance tripping, causes and an innovative solution

Introduction

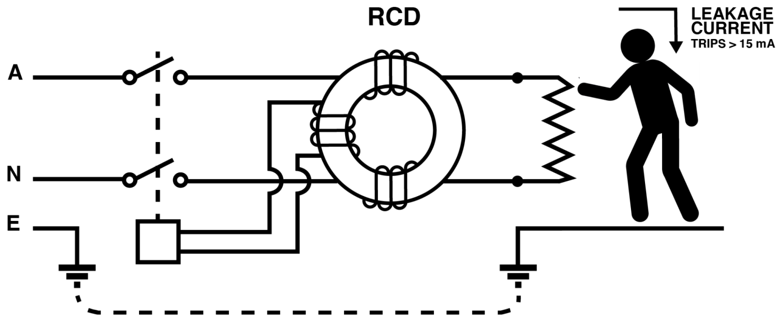
RCDs are used for the protection of life and property and are integrated into most modern electrical installations. RCDs provide valuable safety features to ensure that accidental current through a human body will trip the circuit and remove the voltage from the person. This discussion provides a technical explanation of how the RCD can be tripped by current that is incidental to the core purpose of the RCD and not threatening to life or property. We will examine the problem and the solution to what has become a very concerning issue for those subjected to nuisance tripping of RCDs. For the sake of this study, we will only consider the fundamental frequency of operation.

RCD operation

RCDs are designed to trip when an imbalance occurs in the current flowing through the active and neutral conductors. An imbalance normally means that some form of leakage current is flowing from the active to the earth, bypassing the neutral circuit. This could happen if a person or animal touched the active circuit and permitted current to flow through the body of the person or animal to earth. If this current were allowed to continue to pass through the body, death would quickly occur.



An imbalance could also mean a conductive path has been established between active and earth through insulation breakdown. In this case the current may cause heating and ultimately fire if left unchecked. When the RCD trips, the current stops flowing and the likelihood of fire is reduced. The current flowing due to accidental human misadventure or insulation breakdown is predominantly in phase with the voltage because the load in this case is mainly resistive.



The current flowing through the RCD is constantly monitored for a balanced state and when the imbalance reaches a certain level, the RCD trips causing the load circuit to de-energize. RCDs are manufactured at various trip currents but for the sake of this study we will concentrate on the 30mA RCD rating. This means that the nominal trip current imbalance has an *upper* limit of 30mA. While this is the nominal trip level, the RCD can trip at half of this level and remain within manufacturers specifications.

In practice, it is common to see an RCD trip at about 66% of the nominal trip rating. This means that a 30mA RCD can trip at 15mA and still be within the manufacturers specification but as a generalization, in practice they can typically trip at about 20mA. If the RCD is operating very close to the trip point, when final loads are switched on, the transient leakage current invariably trips the RCD. In this case loads must be managed to keep those currents below the trip threshold.

When designing systems, it is common to use a rule of thumb of allowing leakage currents of about 33% of the nominal RCD rating for reliable operation. This means for an RCD of 30mA nominal rating, steady state leakage current should remain below about 10mA for reliable operation. If the RCD can, according to the specifications, trip at 15mA, the 10mA rule provides for a *trip margin* of 5mA. If the steady state design leakage current exceeds 10mA, it is common for the load to be split across another RCD to divide the leakage current across two circuits to segregate the leakage currents into manageable levels.

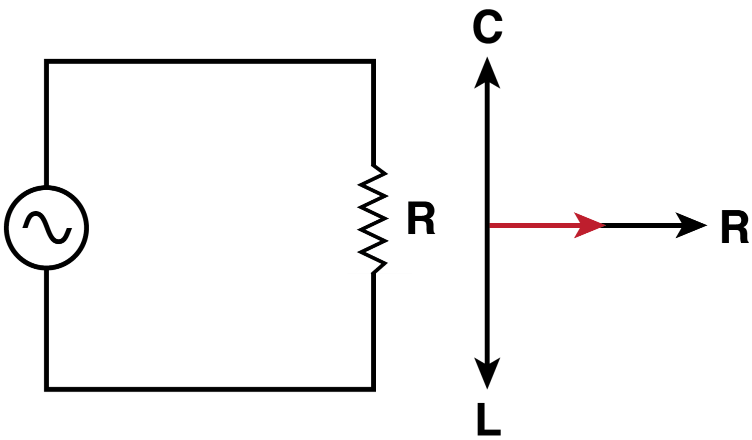
Splitting the loads across two RCDs is practical in some installations, but in other cases it is impractical. An example where segregation is difficult is the case of a boat at a marina, powered from a single outlet, protected by a single RCD on the dock. In this case the leakage component cannot be spread across multiple RCDs easily.

Different types of load.

Resistive

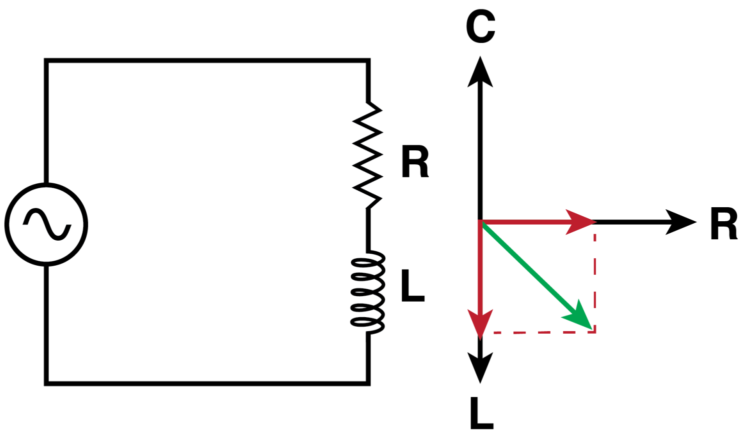
Electrical loads have varying characteristics of resistance, inductance or capacitance. Consider a load of an appliance like a toaster. The current flows through the element producing heat. The electrical characteristic of that load is predominantly resistance.

If we were to observe the phase relationship between the voltage and the current for the toaster, they would be in phase as shown on the vector diagram. The resistance causes no phase change between voltage and current.



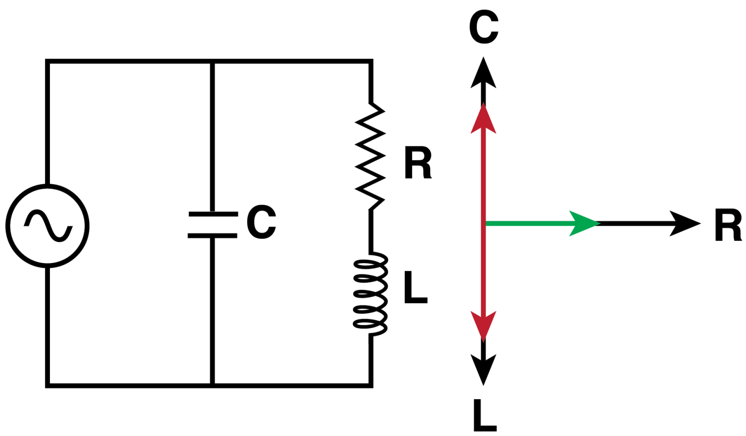
Inductive

Now let's consider the electrical characteristics of a motor. A motor generally has an element of resistance but also an element of inductance. With both resistance and inductance the relationship between the voltage and the current changes in accordance with the magnitude of resistance and inductive reactance. The current lags the voltage by an angle determined by that relationship. If the load were purely inductive that phase angle would be -90 degrees.



As inductive loads cause a change in the current phase angle, in the case of high power loads the energy authority can require that the phase change, or *power factor* be corrected.

To correct for the excessive lagging power factor of the inductive load, capacitors are used to bring the power factor back to an acceptable level. The capacitor compensates for the inductive reactance, bringing the current back in phase with the voltage.

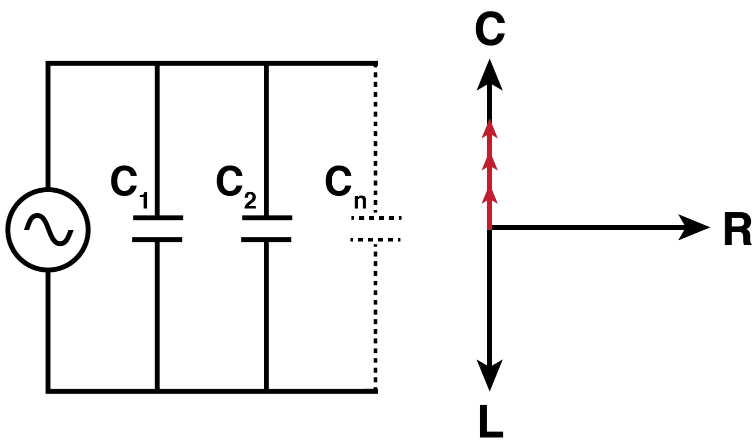


By simply putting appropriately sized capacitors in parallel with the motor the power factor is changed to compensate for the inductive load. The only load component to dissipate real power is the resistor because both the inductive and capacitive loads are presenting purely reactive loads.

In this case we have corrected a power factor problem by introducing a reactive load of opposite phase into the circuit, in parallel with the original load. Notice the inductive reactance and the capacitive reactance are equal and opposite, cancelling and only leaving the in-phase resistive component.

Capacitive

In modern electrical circuits, we also see small capacitive loads, even if the appliance or load is not switched on. Cabling has an inherent capacitance by virtue of the separation of conductors by an insulator, but this capacitance is relatively small.

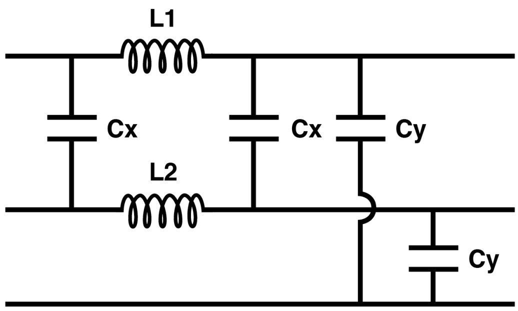


In many cases however, capacitors are deliberately included in the mains circuit. These are to provide a reduction of electromagnetic radiation called *conducted emission* for devices that have the potential to cause Electromagnetic Interference (EMI). The widespread use of switch mode power supplies has required the introduction of these filters to comply with Electromagnetic Compatibility (EMC) regulations in most jurisdictions. Many of these devices in parallel contribute to the leading phase angle current as shown in the phasor diagram. As they are on the mains input to a device we have shown the capacitive current for the devices even when the device is switched off. That is why no resistive or inductive vector is shown. As can be seen on the diagram, each small capacitor contributes to the overall leading phase angle current.

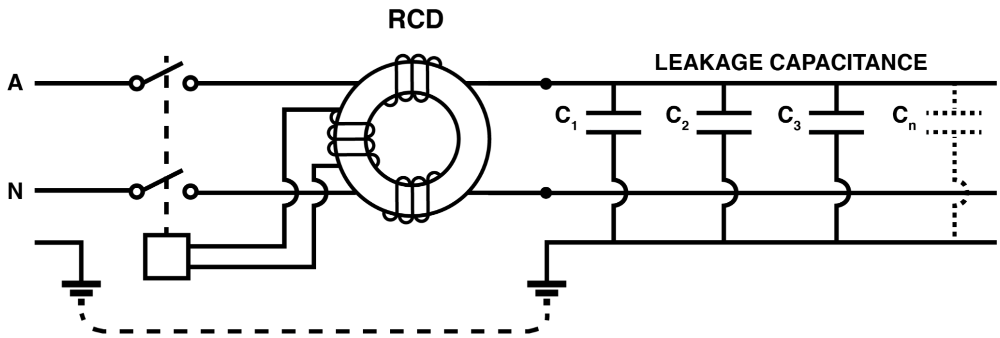
If for example we consider a simple EMC filter on a typical IEC input socket it is specified to have a maximum leakage current of 0.5mA. This is a very basic device and that type of filter is common. An analysis of this device can be found in Appendix A. In isolation each of these single filters provides no practical problem at all. The capacitances are so small that at 50Hz, their impact is minimal. When many are paralleled however, the accumulated leakage current becomes significant relative to the trip threshold of the RCD.

EMI FILTER

From a design perspective, if we accept the maximum leakage per unit as 0.5mA and we need to keep our accumulated leakage current below 10mA, we could only have 20 individual units powered through the one RCD. This restriction has nothing to do with the current carrying capacity of the service but is imposed by the unintended consequences of EMC compliance.



Not all devices have these filters and not all equipment has significant leakage current through capacitive coupling. We generally accept a leakage current for a single unit of equipment of up to about 3.5mA as reasonable. Above that we may be concerned it is taking too much "trip margin" away from the design of the RCD but even 0.5mA leakage per device soon accumulates to the point of RCD tripping.

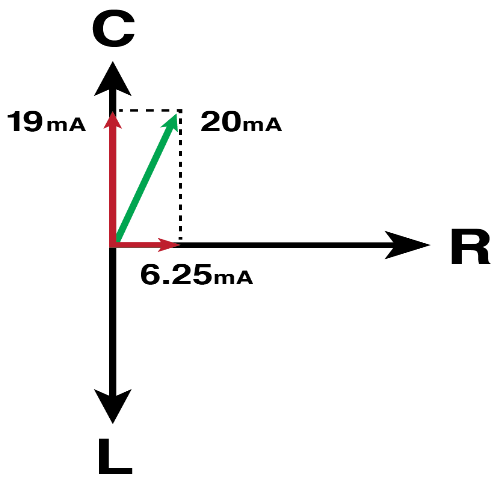


Reference to Appendix B shows a real case example of accumulated leakage currents from a 20 metre motor yacht. This table shows the variations in leakage current for various devices on this yacht.

It is important to understand that capacitive leakage occurs, not because of a fault or design failure but simply because of EMI filters and other stray capacitances. If we accept that a service should be protected by a 30mA RCD and we acknowledge that the RCD can trip as low as half of the nominal value, we have a restrictive design limitation of the number of devices we can power from the RCD, even with absolutely no fault present. This incidental current resulting from EMI filters and other stray capacitances limits our design because of an accumulation of many small currents all at 90 degrees to the voltage.

We have considered the most basic filter available for EMC compliance, but sometimes more advanced filters are required to reduce common mode and differential mode conducted emissions for variable frequency drives and other high frequency switching applications. These more advanced filters can offer greater leakage current than the basic design previously shown.

The RCD trips on the magnitude of the leakage current. The magnitude of the leakage current is the vector sum of all currents. The vector associated with capacitive reactance discussed earlier, is leading the voltage by 90 degrees. We know these small leakage currents are not a fault and we know they do not dissipate power as they are purely reactive. They do however impact on the resistive leakage trip margin as the RCD trips on the magnitude of the combined vector.



Note in the case of an accumulation of capacitive currents, the resistive trip margin is reduced. As an example, if we accept the RCD trips at a current of 20mA, and 19mA of capacitive current is already flowing, only 6.25mA of resistive current is required to trip the breaker.

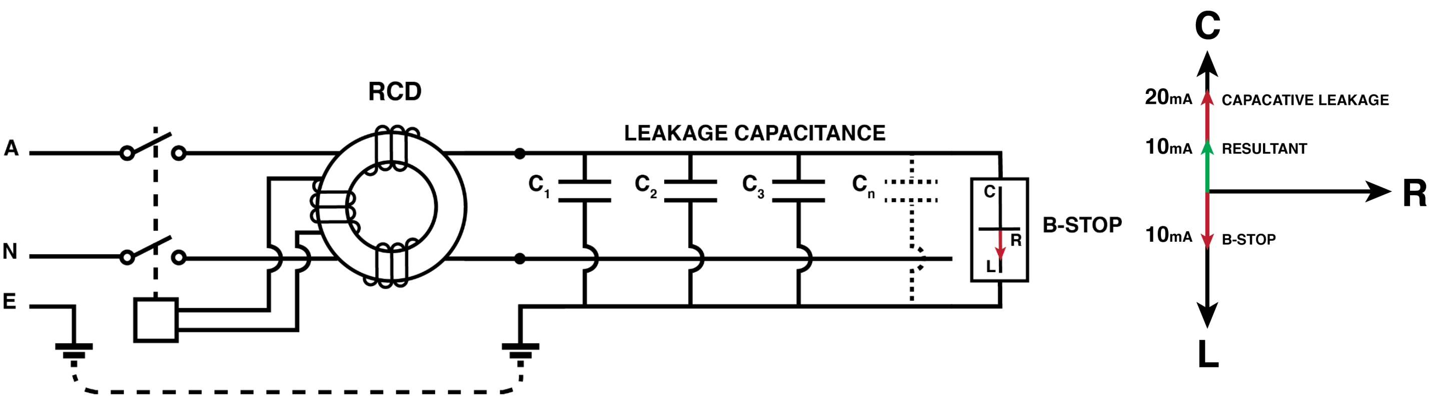
RCD “nuisance tripping” solutions generally centre on changing the characteristics of the RCD, not the load. Changes like trip time delays and various techniques shaping the RCD frequency response are used. Further segregation of circuits using multiple RCDs is considered good practice to spread the leakage current across multiple RCDs.

In some jurisdictions, the magnitude of the RCD tripping point can be adjusted to allow for the steady state combined leakage. The baseline leakage is measured and an offset is used to establish a sensible trip margin. This could be a risky practice because if all loads are removed, the RCD is now set to trip at a higher leakage current than the preferred 30mA. It will only provide the specified protection as designed if the leakage producing loads remain connected.

Resolution

From an engineering perspective, it would be ideal if we could simply remove the capacitive leakage as it represents no fault, and is simply an anomaly that causes a loss of trust and in some cases workarounds to resolve nuisance tripping. It is an unintended consequence of the need to reduce electromagnetic interference. It is simply an unfortunate side effect of trying to improve EMC.

We know however, we cannot remove the capacitive leakage current, but what if we could reduce it by introducing an inductive current? Why not use the same principle as commonly used and previously outlined for power factor correction to regain a reasonable trip margin of the RCD? In power factor correction we change the power factor of an inductive load by introducing capacitive current. What if we introduced a small amount of inductive current to cancel the steady state capacitive leakage current? If this were possible the capacitive vector can be reduced by an amount we specify. Let's make it 10mA.



The choice of inductive current level is important because too little does not nullify the capacitive current sufficiently. Too much (say over 20mA) and the RCD will trip because of inductive current if all other loads are disconnected. In that case the RCD would trip if all breakers on the switchboard were opened. What is required is a midpoint where the trip margin is restored without causing a problem because of the introduced inductive current vector.

Until now the creation of a small, purely inductive current to counter the capacitive current has been impractical to implement. Reference to Appendix C shows that to provide a 10mA inductive current at 50 Hz we would require an inductor of 76 Henries, certainly a situation that is not physically realizable as such an inductor would be physically huge. The B-Stop is shown in the diagram to convey the idea of introducing a small inductive current to neutralise the impact of the capacitive leakage resulting from EMC filters. We do not advocate using an actual inductor for this purpose. We do however now have a device that can provide that function by simulating that inductance and applying that simulated inductance between Active and Earth. This device cleverly uses active components to provide a small current 180 degrees out of phase with capacitive leakage current.

This device does not impact on the reaction time of the RCD to resistive leakage currents, restores trip margin and is simply installed as another load on the service, similar to the way capacitors are added to inductive loads to correct for power factor. In the simplest implementation it can be plugged into a GPO or if required can be installed into the switchboard permanently. It is an active device and is connected to Active, Neutral and Earth. It has a selector jumper to introduce 5mA or 10mA of inductive current.

Importantly, no change at all is required to the RCD wiring. The original design integrity of the installation is maintained. This device does not provide any reduction of RCD sensitivity to resistive leakage currents. It is simply an additional load to the existing circuit.

Conclusion

In the marine industry, nuisance tripping can cause boat owners losses if their vessel is unattended. In some cases, segregation of multiple RCDs is not practical. Nuisance tripping can cause a loss of trust in the important safety mechanisms imposed through regulation. This device can restore trip margins in existing installations simply, at a reasonable cost and maintain the integrity of the safety features of the RCD.

This device provides an innovative solution to assist in the resolution of the common problem of nuisance tripping. The installation is easy, the results of the addition of this device can be measured with basic equipment and improvement to RCD reliability and performance is immediate. Importantly, the operation of the RCD is not changed with regard to protection of life and property.

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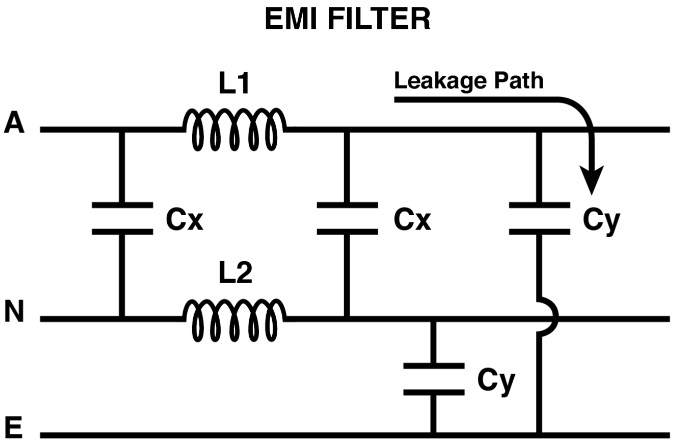
Appendix A

Typical EMI filter



This filter provides simple attenuation of conducted emissions in the radio frequency spectrum. Both Cx capacitors attenuate differential mode signals and both Cy capacitors attenuate common mode signals.

Consider the path from the Active circuit to earth. Current flows through the inductor L1 and through the Capacitor Cy. The inductor has a very small value and minimal reactance at the mains fundamental frequency of 50 Hz. The value of the inductor is typically about 1.2 mH and the value of Cy can be 4.7nF.

If we calculate the inductive reactance of L1 we see that

$$Xl = 2\pi f L$$
$$Xl = 314 \, x \, 0.0012$$
$$Xl = 0.41 \text{ ohm}$$

Capacitor in series with the inductor to earth is 4.7nF

Capacitive reactance for a 4.7nFarad capacitor used in an EMI filter at 50 Hz.

$$Xc = \frac{1}{2\pi \, fc}$$
$$Xc = \frac{1}{6.28 \, x \, 50 \, x \, 0.0000000047}$$
$$Xc = 677 \, k\Omega$$

The reactance of the inductor can be ignored as 0.41 ohm is immaterial compared to the capacitive reactance of 677 $k\Omega$.

Leakage current through 4.7nFarad capacitor used in EMI filter at 50 Hz.

$$i = \frac{240}{677{,}000}$$
$$i = 0.35 \, mA$$

Each EMI filter at 50Hz contributes 0.35mA to the accumulated leakage current.

Appendix B

20 Metre Motor Yacht Leakage currents in mA.   Tested August 2021

	Circuit	Band Pass filter on	Band pass filter off
Location			
Saloon Switchboard			
	Main Batteries Charger	0.837	0.903
	Genset Batteries Charger	0.31	0.34
	VAC Cabin Sockets	0.39	0.41
	VAC Saloon/Galley Sockets	0.52	0.55
	VAC Heads Sockets	0.215	0.227
	Range	0.076	0.2
	Galley Exhaust	0.54	0.57
	Dishwasher	0.8	1.4
	Water Heater	0.077	0.088
	Oven	1.352	1.4
	Barbeque	0.406	0.425
	Galley Fridge	0.195	0.235
	Cockpit Fridge	0.245	0.262
	IceMaker	0.358	0.376
	Telecommunications	0.18	0.187
	Lower Deck Fan Coils	1.4	2.2
	Main Deck Fan Coils	1.18	3.6
	Hifi	1.3	1.5
	Total for Saloon Switchboard	***10.381***	***14.873***
Crew Cabin board			
Bus A			
	AirCond	0.67	0.72
	Water Maker	0.112	0.116
	Sea Keeper	3.3	4
	Washing Machine	0.044	0.047
Bus B			
	QAC2 Saloon Board	-	-
	Eng RM/Crew Sockets	0.112	0.12
	Curtain Inverter	0.08	0.1
	Total for Bus A and B	***4.318***	***5.103***

Switchboard and Bus A and B add to 14.873 + 5.103 = 19.976 Total.
Generator RCD tripped at 21 mA as measured on min max measurement with all loads on.

Appendix C

In order to correct for current caused by capacitive reactance, an appropriate amount of inductive reactance needs to be introduced. If we are trying to correct for 10mA of capacitive current, we need to establish what inductance is required.

Compensating Inductance required for 10mA at 240 volt AC.

$$Xl = \frac{E}{I}$$

$$Xl = \frac{240}{0.01}$$

$$Xl = 24\ k\boldsymbol{\Omega}$$

$$Xl = 2\boldsymbol{\pi}\ \mathrm{fL}$$

$$24\ k\boldsymbol{\Omega} = 6.28\ x\ 50\ x\ L$$

$$L = 76\ \text{Henries}$$