Ground Fault Circuit Interrupters (GFCIs) for AC & DC Systems

This article has been written mainly with North American users in mind, and is intended to provide readers with practical information on the operation and selection of GFCIs. We would welcome responses to the article, favorable or otherwise, so that we can learn from our readers.

The international version of this article is entitled Demystifying RCDs and can be seen at www.rcd.ie.

See sister articles: Leakage Current Detection for AC & DC Application.

Starting With Some Acronyms

UL: Underwriters Laboratory
CSA: Canadian Standards Association
IEC: International Electrotechnical Commission
GFCI: Ground Fault Circuit Interrupter
RCD: Residual Current Device (IEC term for GFCI)

GFCI Product Standards

The most relevant standard for GFCIs in the USA is UL943.
For Canada it is CSA C22.2.
For Mexico it is NMX-J-520.

Although the numbering is different in each case, the three countries share the same basic GFCI requirements.

A GFCI (ground fault circuit interrupter) is intended to provide protection against electric shock. It does this by opening one or more contacts to disconnect power from a circuit or load when the ground fault current flowing in the circuit protected by the GFCI reaches the rated operating current of the GFCI.
GFCIs for AC & DC Systems

Figure 1 shows a typical 120V single phase configuration. Under normal conditions the current $I_L$ flowing from the supply to the load will be equal to the current $I_N$ flowing back from the load. Because these currents are of equal magnitude but flowing in opposite directions within the current transformer (CT), their vector sum will be zero and the CT will produce no output. If a person touches a live part as demonstrated in Figure 1, an additional current $I_g$ will flow through the person’s body to ground and return to the supply via the ground or earth return path. The current $I_L$ will now be greater than $I_N$ by the value of $I_g$ and the CT will produce a resultant output in response to this differential or residual current. This output will be sensed by the electronic circuit, and if it is above a predetermined level (typically 6mA) it will cause the GFCI contacts to open and disconnect the supply from the load and thereby provide protection. The differential current level at which the GFCI is designed to operate is known as its rated ground fault operating current, and can be designated as $I_{\text{gn}}$, a term widely used in IEC documents.

Figure 2 shows a typical 240V two line arrangement. In this case the voltage across L1 and L2 is 240V and this supply is used to supply high power loads, e.g. water heaters and cookers, etc. The centre of the supply transformer is connected to ground and this centre point is distributed as a neutral conductor. The voltage between N and L1 or L2 will be 120V, and this supply is used to power smaller loads, e.g. receptacle outlets and lighting circuits, etc. In this arrangement, all three current carrying conductors are passed through the CT. Under normal conditions the vector sum of all currents flowing through the CT will be zero. However in the event of a ground fault a differential current will flow back to the supply via earth, bypassing the CT. When this current exceeds the operating threshold of the GFCI the supply to all loads will be disconnected. In some GFCIs, the neutral may also have a switchable contact.

It is worth noting that in this system the maximum touch voltage is 120V even though the installation uses a 240V supply.
In the case of GFCIs, a ground fault current therefore refers to any current other than the load current. The ground fault current may flow through a person’s body or through a fault in equipment or wiring anywhere on the load side of the GFCI. The key factor in the ability of the GFCI to detect a ground fault current and provide protection is the connection of the supply neutral conductor to earth at the origin of the installation.

Although the load current will typically be in the amperes range, the differential current \( \Delta I \) will generally be in the milliamps range. Typical maximum values of \( \Delta I \) in the USA are 6mA for personal shock protection, 30mA for equipment protection, and 300mA for fire protection.

It is worth noting that the normal human body resistance for most people is in the range 1000 - 2000 Ohms, but for some people it may be as low as 500 ohms, so for a touch voltage of 120V the current through the body will generally be in excess of 50mA.

6mA versus 30mA Operating Thresholds.

In the USA, the operating threshold for a GFCI for personal shock protection is 6mA. In most of the rest of the world, the threshold is 30mA. There are two reasons for this difference. The first relates to safety, and the second relates to technology.

Tests on the human body have indicated that as the current is increased from zero mA, muscles tend to seize at about the 10mA level with the result that a person touching a live conductor may not be able to let go a live conductor at currents above 10mA. This is referred to as the “let-go” limit, and the North American GFCI standards decided to set the operating level of GFCIs at 6mA so as to have a comfortable safety margin below this threshold. At about 40mA, heart fibrillation starts to occur, which could lead to heart failure. European manufacturers decided to set 30mA as the operating level of RCDs (GFCIs) so as to have a comfortable safety margin below this threshold. This begs the question as to why the Europeans would set a higher level than the let-go level. The answer is Technology. North America uses electronic technology in their GFCIs, and it is relatively easy to set an operating threshold of 6mA for such devices. However, most European devices use electromechanical technology, and it is extremely difficult for such devices to operate at the 6mA level, so they chose 30mA because they can detect this level quite easily and it provides protection against heart fibrillation. European manufacturers had a substantially greater influence on IEC standards and practice, and the 30mA level has been adopted in most areas worldwide with the exception of North America.

(See IEC60479 for more detailed information on the effect of current on the body)

Double Grounded Neutral (DGN) Problem

Figure 1 showed a typical situation whereby the GFCI provides protection. However, a condition that could prevent the GFCI from providing protection is represented in figure 3 below.
This condition could arise due to miswiring or insulation breakdown. The fault current $I_g$ will flow through the body as before, but will now split into two currents, $I_{ge}$ and $I_{gn}$, with $I_{ge}$ flowing back to the supply via the earth or ground return path, and $I_{gn}$ returning back to the supply via the DGN fault connection and the neutral conductor. The ratio or division of these two currents will depend on the impedance of the neutral and ground paths. In many installations, the ground wire could be of smaller cross sectional area than the neutral wire with the result that $I_{ge}$ will be smaller than $I_{gn}$. In any event, the CT will no longer see the total fault current and will only see $I_{ge}$, and if $I_{ge}$ is less than the trip threshold of the GFCI, the device will not trip.

UL943 requires GFCI manufacturers to provide an effective solution to this problem in that the GFCI must trip automatically or continue to provide protection under this condition. Figure 4 shows one example of how this can be achieved, but other means are also used in practice.

In the arrangement of figure 4, there is a second current transformer, CT2. Connected to this is an oscillator circuit which induces a current into CT2 winding. In this example, the oscillator produces a continuous current $I_{osc}$ into CT2 winding. Under normal conditions, this current does nothing. However, when the DGN fault occurs, a loop is formed by the neutral and earth paths, and $I_{osc}$ is induced into this loop. CT1 sees $I_{osc}$ as a fault current and trips the GFCI. The DGN detecting circuit can function without an earth fault and without a load connected.
The DC system may be totally isolated from ground, or may have one side connected to ground. If one side is connected to ground as shown by the dotted line, a person touching the +ve side of the supply will be exposed to a shock risk. In the case of a totally isolated system, if one side becomes inadvertently grounded, e.g. because of a first fault, a person touching the opposite side of the supply will be exposed to a shock risk. In either case, if a ground fault current above a certain level flows in the circuit, this will be detected and cause automatic opening of the contacts.

It may seem strange to use a current transformer to detect a DC ground fault current. However this is achieved by driving the CT core into and out of saturation at a certain frequency, and using the DC fault current to generate a detectable change in the saturation characteristics.

**DC Sensing GFCIs**

DC ground fault currents can occur in installations powered from DC, such as
- Mines
- Tunnels
- Solar panels
- Electric vehicles
- Ships
- Aircraft, etc.

DC currents through the body can be every bit as dangerous as AC currents and GFCI protection should be provided where shock risks exist. In IEC, GFCIs/RCDs that provide protection against both AC and DC ground fault currents are referred to as B Types.

Commercial: Western Automation (WA) can provide GFCI solutions in the form of technology or GCFI products for use in AC & DC systems.
Types of GFCIs

GFCI types can be categorised based on their construction, performance or configuration etc, as follows.

Mounting

- Panel Types – e.g. installed in panelboards
- Receptacle Types – a receptacle incorporating a GFCI
- Portable Types - fitted in a plug, an adaptor, or in a cord.

The panel type GFCI may be single phase or three phase whereas the receptacle and portable types are generally single phase only. The panel types generally provide protection for part of or a complete installation. The receptacle and portable types provide protection for loads connected directly to the device. For this reason they are sometimes referred to as “point of use” GFCIs. Receptacle types provided with feed through terminals may also be used for protection of downstream receptacles. This is normal practice in the USA.

Contacts

The GFCI figures shown in this document have two contacts in each case. However, in practice, single pole GFCIs tend to use a single contact in the live pole, and an unswitched neutral pole. Portable GFCIs and receptacle based GFCIs break all poles.

AC or DC Sensing

GFCIs may also be categorised based on the type of ground fault current they can detect, e.g. detecting AC only, or detecting AC & DC fault currents.

Trip Levels & Trip Times

GFCIs covered by UL943 are known as Class A devices because their specified trip level ($I_{tn}$) is in the range 4 – 6mA. The trip time specified in UL943 for GFCIs is derived from the following formula.

$$T = \frac{20}{I^{1.43}}$$

Where $T$ = time in seconds

$I$ = ground fault current in milliamps

The GFCI trip threshold combined with its response time are the most critical factors in minimising the risk of heart fibrillation and thereby providing protection of human life against the effects of electric shock. These two factors are addressed by the above formula. It is not easy to figure out from the formula what the trip time should be for say, 6mA, 20mA or 50mA, so we have produced figure 5 below to show the relationship between fault current and trip time.

The graph provides a ready indication of the maximum trip time in relation to a given ground fault current. In practice, most GFCIs operate in less than 100mS regardless of the fault current level.

Figure 6 - Maximum trip time in relation to a given ground fault current
Method Of Latching

Latching is the means by which the contacts of the GFCI can be closed and held closed. GFCIs fall into the following two broad categories:

**ML** types that are **Mechanically** or **Magnetically** latching, and **EL** types that are **Electrically** latching.

The ML device contacts can be closed and will remain closed regardless of whether or not a supply is present. The ML device may cease to operate in the event of loss of supply neutral. (see Problems with GFCIs)

The EL type requires the presence of a supply above a certain voltage to enable its contacts to be closed (manually or automatically), and when the supply is reduced below a certain level the contacts open automatically.

**EL** types fall into two categories: **ELR** and **ELO** types.

The **ELR** GFCI opens automatically on loss of supply but recloses automatically on restoration of the supply (electrically latching and automatically reclosing when power is restored). It therefore provides protection against loss of supply neutral, but also recloses once the supply is restored. The **ELO** GFCI opens automatically on loss of supply and remains open on restoration of the supply (electrically latching and remaining open). The ELO also provides protection against loss of supply neutral. However, the ELO response is generally used in portable type GFCIs, and is not considered suitable for applications where power needs to be restored to equipment such as refrigerators, etc.

**Testing** (see Problems with GFCIs)

GFCIs are fitted with a test button to enable users to test the GFCI from time to time. In fact it is recommended that the GFCI be tested on a regular basis because if a GFCI fails for any reason, the user will not be aware of the failure unless the test button is operated. (see: Reliability – Design Factors)

**Selecting GFCIs**

Factors such as the rated voltage, load current, residual current and number of poles should be fairly obvious, so I will deal with some other factors.

1. **AC, Rectified AC and DC**

   In order to choose a GFCI the user or installer should first of all decide on the type of protection required. As an absolute minimum requirement, all GFCIs will provide protection against AC ground fault currents. However, if any type of power control is used on the load, e.g. speed control for electric drills, heat control for hair dryers or heaters, dimmer control for lighting, partial or complete rectification of the AC supply will be used within the equipment, and this could result in a ground fault current that is not pure AC, but rectified AC. Figure 6 shows examples of typical wave shapes produced by power controlled equipment.
UL943 requires GFCIs to provide protection in the case of wave shape 1 only, but does not presently contain any requirements or tests for protection against the fault currents represented by 2, 3, 4, 5 or 6.

In IEC, RCDs (GFCIs) that provide protection against earth fault currents represented by wave shape 1 above are referred to as AC Types, and RCDs (GFCIs) that provide protection against earth fault currents represented by all of the above wave shapes are referred to as A Types. The use of A Type GFCIs is mandated in several countries such as Germany and the Netherlands, etc. because they believe that AC Type GFCIs do not provide adequate shock protection.

Another important point is that wave shapes 4, 5 & 6 have very fast rise times which can cause voltage or current spikes which may contribute to nuisance tripping in some GFCIs even in the absence of a fault. Some GFCIs can detect all of the above fault currents, but in any event it is also important that the GFCI is not prone to nuisance tripping in the presence of such wave shapes under non-fault conditions.

Commercial: WA offers GFCIs meeting the above requirements.

Problems With GFCIs

Whilst it is readily acknowledged that GFCIs provide a very high level of protection against electric shock, they can unfortunately suffer from some problems, mainly as follows.

1. Miswiring
2. Failure of user to test the device
3. Loss of supply Neutral
4. Poor Reliability
5. Nuisance Tripping

1. Miswiring Problem for GFCI with feedthrough terminals

Figure 8 – Correctly wired GFCI with feedthrough terminals
If the GFCI with feedthrough terminals is miswired as shown in figure 2, the GFCI will appear to provide protection because when the contacts are manually closed and the test button is operated the GFCI contacts will open. However the GFCI will not provide protection in the event of a person touching a live conductor at the integrated socket outlet.

**Figure 9 – Incorrectly wired GFCI with feedthrough terminals**

**Commercial: WA GFCIs cannot be closed if miswired.**

### 2. Failure of user to test the device

Field studies carried out in several countries worldwide, including the USA, have indicated that about 2 – 3% of installed RCDs/GFCIs were defective. In general the users were not aware of these failed devices because they did not test them regularly.

UL now requires panel mounted and receptacle based GFCIs to indicate “end of life” if the device fails to trip when the test button is manually operated. It is expected that UL will also introduce requirements for self testing of GFCIs whereby the GFCI will carry out a test on itself at regular intervals and provide indication to the user of “end of life”.

**Commercial: WA GFCIs incorporate self testing of the device and end of life indication.**

### 3. Loss of supply Neutral

ELO and ELR type GFCI will open automatically on loss of supply neutral and therefore mitigate any shock risk under this supply condition. However, the ELO type needs to be manually reclosed after restoration of the supply, and this precludes its use in receptacle based GFCIs.

The ML type GFCI will remain closed on loss of supply neutral but may not be able to provide protection under this condition if the live supply conductor is still connected. The risk of electric shock under this condition is considered to be minimal, but users should be aware of it. When the supply neutral is restored, the ML type will automatically provide protection again.
4. Poor Reliability
Reliability is largely a function of design and use.
A poorly designed GFCI will lead to poor reliability even if used as intended. However a well designed GFCI will generally be highly reliable when used as intended, but unfortunately its reliability may be compromised when used in unsuitable applications. Examples of unsuitable applications are cases where a GFCI intended for indoor use is used in areas with harsh environments, for example industrial areas or outdoors near swimming pools and farms, etc.

**Commercial:** WA offers GFCIs for harsh environments – See below.

**GFCI for outdoor use.**

![GFCI Image]

The above figures show a GFCI with a duplex receptacle fitted in a weather proof box.
This product has the following unique features.

1. If the cover of a standard weather proof box is left open, the weather proof properties will be compromised. This box is fitted with an interlock to alert the user to when the cover is open.

2. The GFCI is fully visible and accessible from the outside of the box, so it is easy to see the status of the GFCI at all times, and to Test and Reset it as required.

3. The GFCI is fitted with STEOL (Self Test & End Of Life) functionality. The GFCI will carry out a Self Test every 2 – 3 seconds as indicated by the ST LED, and in the event of GFCI failure, the EOL LED will light. The GFCI will automatically trip in the EOL state and remove power to the outlets.
5. Nuisance Tripping

As far as users are concerned, the single greatest problem with GFCIs is nuisance tripping. Nuisance tripping can be a frustrating problem for the user.

Nuisance tripping problems can usually be attributed to the product itself or the protected circuit. Electrical disturbances such as voltage transients occur continuously on the mains supply and can be caused by lightning or by switching. These disturbances can occur upstream or downstream of a GFCI, depending on its location in the installation. The protected circuit may have loads that produce voltage transients due to manual or automated switching (see reference above to wave shapes 4, 5 & 6), or loads that produce high inrush currents. A well designed GFCI should be able to tolerate such non fault occurrences, so in these cases the problem of nuisance tripping lies with the GFCI designer/manufacturer.

Loads on installations may use RFI filtering to avoid inducing noise on to the mains supply. Such filtering can result in transient or standing leakage currents to ground. These problems can usually be traced to a specific load, e.g. washing machine, dish washer, etc. In North American homes most GFCIs have a trip level of 4mA - 6mA. A typical electrical appliance may produce a standing leakage current of 3 – 4mA which effectively primes the GFCI to trip. It could take just another 1 – 2mA from another load to trip the GFCI. In such cases the best solution may be to provide a dedicated point of use GFCI to protect that load.

Nuisance tripping problems can often be resolved by selecting GFCIs with high immunity to nuisance tripping. This problem can also be alleviated by using GFCIs to protect separate circuits or subcircuits rather than an entire installation. Ideally, GFCIs should be used at the point of use because they will then be protecting a specific load rather than an installation. Portable and receptacle based GFCIs are ideal “point of use” devices.

Commercial: WA Corp offers GFCIs with high immunity to nuisance tripping.

About the author.

Pat Ward is the owner manager of Western Automation R & D based in Ireland and President of WA Corporation USA. WA Corp is a specialist designer and manufacturer of GFCI technology & products for OEMs in the North American market. Pat has been an active member of technical committees in ETCI, IEC and CENELEC since 1991 and has been involved in the drafting of several international standards for GFCIs, AFCIs and LCDIs and has also participated in working groups within IEC addressing problems of reliability and EMC requirements for GFCIs and AFCIs, etc.