GROUND FAULT PROTECTION IN LOW VOLTAGE SOLIDLY GROUNDED WYE SYSTEMS, NEED FOR PROTECTION AND THE NEED FOR RELIABILITY

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***Abstract* -** Reliable power distribution systems require adequate protection and adequate protection requires reliable protection systems. The need for ground fault protection in low voltage solidly grounded wye systems is well documented in literature, standards and has been part of the national electrical code (NFPA 70) since 1971.

The potential effect of ground fault protection on system reliability is a realistic concern, hence the various references indicating when ground fault protection is to be used and not to be used or recommended. How to mitigate the potential negative effects on system reliability is treated in article 517.17 of NFPA 70 (2005). Recent changes in NFPA 70 have made the complexity of LV ground protection and system reliability more prominent.

This paper will provide an overview of why LV ground fault protection became the standard we take for granted today. Additionally, the author will summarize some of the key descriptions of arcing fault in industry literature as well as descriptions in current standards that define the devices and protection commonly used today. Key aspects of how devices respond to fault current will be discussed. Finally, the author will provide an analysis of selectivity and system reliability issues involving ground fault protection.

Index Terms — Low Voltage Ground Fault, Selectivity, Arcing Ground Fault, Arcing Fault

I. INTRODUCTION

Throughout the 1960's an increase in electrical equipment burn-downs, injuries and fires were noticed. Investigations and research pointed to arcing ground faults as the cause. Arcing-ground-faults, previously rare, became more common due to an increase in use of 480V solidly ground wye systems. Previously, many industrial systems requiring substantial three-phase-power were served with ungrounded delta systems. These systems, though relatively freer of ground fault problems, were susceptible to insulation breakdown issues due to voltage transients. Converting systems to solidly grounded wye distribution controlled the over-voltage transient problems but had the un-intended consequence of creating the arcing ground fault problem. Commercial loads also increased in size during this time. Large loads were easier to serve at 480/277V than the 120/208 or 240/120V that had been used previously. The need to serve larger loads caused the current ratings of main devices to increase making them less sensitive to small arcing fault currents.

All of these changes drove the industry to investigate and eventually mandate solutions for the arcing ground fault problem. In 1971, the national electrical code mandated GF protection for solidly grounded wye systems with 150V or more to ground and service entrance main over current devices rated 1000A or more. In the 2005 NEC this is part of article 230.95 and 215.10. Luckily, ground fault currents are relatively easy to detect and protection systems were devised that can address the risk and mitigate damage.

II. MULTIPHASE BOLTED FAULTS CHARACTERISTICS AND TRIPPING MECHANISMS

A. Bolted Faults and Energy Integrating Trip Mechanisms

Traditional over current protection is designed, rated and selected for its ability to operate under bolted fault conditions. UL 489 and UL1066 test and verify a device's capability to properly sense and interrupt bolted faults of various magnitudes up to the device's short circuit rating. Arcing faults of sufficient magnitude to engage tripping and operating mechanisms can be expected to be easier to interrupt than an inductive bolted fault. This is due to the arc voltage at the fault sharing in the current interruption process and the changes in fault current power factor.

Arcing currents however present greater difficulty for detection because they are lower magnitude, may be non-sinusoidal, may display lower first cycle peaks than RMS equivalent bolted fault currents and may be intermittent. Their destructive effect is larger than their RMS magnitude would indicate relative to bolted fault currents of equal or greater value in RMS terms. Several studies and papers have been written in the last 4 decades on the characterization of low voltage arcing currents. Some based on test data for phase to phase arcing currents and some based on phase to ground arcing currents. From the perspective of equipment damage, arc-flash-energy and safety it is the expected stable arcing-currents which are most important. Based on the presumption that a higher current is easier to detect than a lower current, it is the minimum sustainable arcing current, which is most important during the first cycles of a fault.

The worse case characteristic of a bolted fault may be determined by Eq. 1 when the lowest power factor is used.

$$i(t) = I_{\max}\left[\sin(\omega t+\psi-\theta)-\sin(\psi-\theta)e^{-(R/L)t}\right] \quad (1)$$

Where:

I_{max}	Peak fault current (V_{peak}/Z_{fault})
ωt	Angular frequency times time

Ψ	closing angle (point within cycle at which the fault started)
θ	angle of fault current caused by its X/R ratio (power factor)
R	System resistance
L	System inductance

The above equation yields the asymmetrical fault curve commonly used to describe short circuit faults. That equation is drawn 3 times, each curve displaced by 120 degrees to represent a three-phase system. This can be seen in Figs. 1, 2 & 3, representing a 3-phase balanced bolted fault at a specified power factor and closing angle for phase A. The asymmetry is mostly a function of the fault current's power factor. Which phase or phases display the most asymmetry is a function of the closing angle.

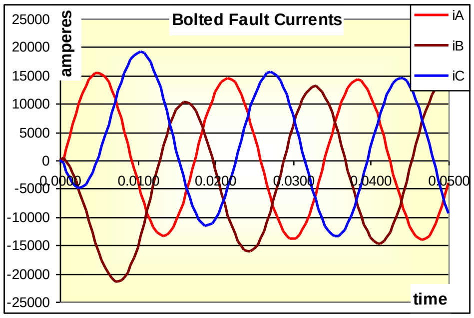

Fig.1 3 Phase fault current -10kA RMS, X/R=4.9 (PF=20%), Ψ_A=0°

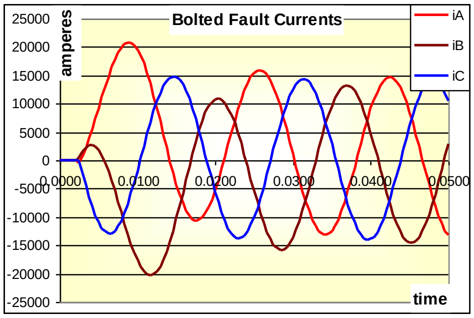

Fig. 2 3 Phase fault current -10kA RMS, X/R=4.9 (PF=20%), Ψ_A=-45°

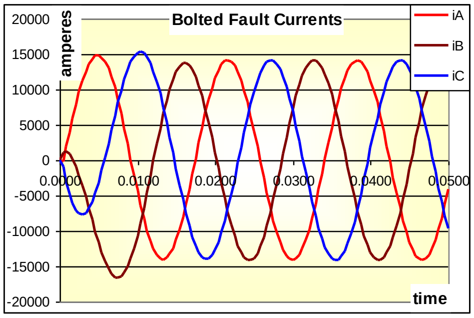

Fig. 3 3 Phase fault current -10kA RMS, X/R=1.73 (PF=50%), Ψ_A=0°

Instantaneous trip mechanisms will respond differently to this type of fault current because the first half cycle of current is quite different from fault to fault and phase to phase, depending on the fault's characteristics and the device's sensing mechanism. Fuses are always thermal energy devices and hence respond to the accumulated I^2t energy provided by the current flowing through the fuse element. They are also single-phase devices causing each fuse to operate independently of the others. The fuses can be said to integrate the area under the curve. Hence, especially, in the instantaneous range they will respond differently to the different phase currents based on asymmetry and closing angle.

Fig. 4 represents the cumulative I^2t experienced by a single-phase overcurrent device during an asymmetrical three-phase fault. Each device accumulates thermal energy at different rates regardless of the fact they are all experiencing what is described as the same RMS current. Depending on the energy requirements for operating one phase or another may trip first. Which phase exhibits the highest peak current, or which phase reaches a peak first may not be correlated with which phase interrupts first.

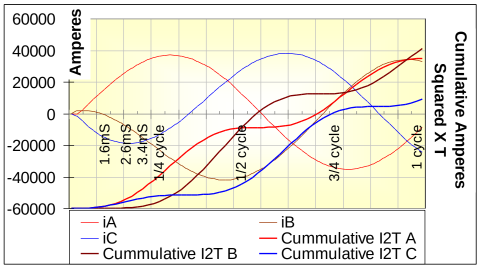

Fig. 4 First-cycle energy accumulation in a three-phase fault current

The long time or short time algorithm in a digital circuit breaker and a thermally activated bimetal tripping mechanism will function in a similar manner. All three mechanisms respond to an accumulated value of energy. During long-time tripping fuses will release heat, as will circuit breaker thermal systems. Digital trips will have cooling algorithms, and programmed inverse-time-slopes, to simulate a mechanical thermal system. All of the short time and long-time trip mechanisms may take several cycles to trip so that the effect of the initial asymmetry is averaged and the RMS value of the current predominates. The main differences between fuses and circuit breakers is that the circuit breaker mechanism may respond to the energy in or current magnitude in one phase, however, all three poles operate together. Fuses will operate independently of each other subject to the exact current flow through each fuse.

B. Bolted Faults and Instantaneous Tripping

Fuses operate similarly in their adiabatic (heat out<<heat in) range as they do in their non-adiabatic range. Hence, they are always energy integrating devices. However, the pre-arc or melting energy, in the adiabatic range is obtained over a very short time period, less than ¼ of a cycle. Since the energy to trip the fuse is collected over such a short time, the asymmetry plays a large role in

determining which fuse will trip first and how long it takes to trip. Hence, the fault power factor plays a big role in determining the current limitation provided by current limiting fuses. The RMS value at which a fuse may be determined to be current limiting increases as the prospective fault current X/R ratio decreases in value. This can be shown by the sample let-through curves shown in Fig 5. For example, a 4000A class L fuse with a current limiting threshold of 55,000A at 15% power factor may have a nominal RMS current limiting threshold of over 100,000A at a power factor of 1.

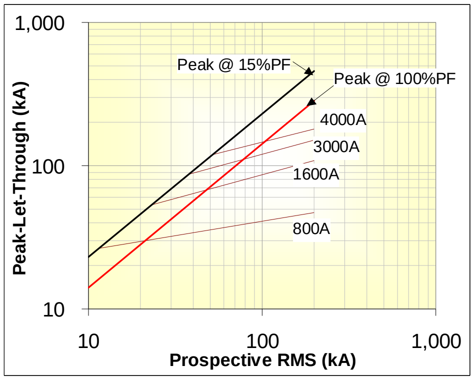

Fig. 5 Typical Class L Fuse let-through characteristics

Circuit breaker trips may operate differently in their instantaneous range depending on the type or combination of types of mechanisms used. Magnetic trips respond primarily to instantaneous current magnitude with some amount of time required to overcome mechanism friction and inertia. Simple electronic-instantaneous trips function by comparing instantaneous samples of current against a defined threshold. The signal may be filtered and a number of data samples may be compared to reduce the likelihood of nuisance tripping. In general, magnetic and simple electronic trips respond to instantaneous current magnitude. The tripping threshold may be set to the expected peak for a power factor 1 sine wave with an RMS value equal to the setting. A circuit breaker set to 10,000A RMS instantaneous pick-up is set to a trip threshold of 14,100A. Blow-open contacts using a reverse loop configuration will also respond to current magnitude. The current must last long enough to sufficiently propel the mechanism and commit the circuit breaker to tripping. A circuit breaker's instantaneous response will therefore be more sensitive to a highly asymmetrical (inductive) fault than it will be to a symmetrical (resistive) fault. A coordination study may or may not consider the effect of asymmetry on instantaneous tripping.

In summary, most circuit breaker instantaneous-operating-mechanisms operate based on instantaneous current magnitude compared to a threshold level. Fuses operate based on accumulated energy that is proportional to the square of current over time. This may yield operational differences between different types of circuit breakers and fuses operating near their instantaneous thresholds or current limiting thresholds depending on the asymmetry of the fault current.

III. BASICS OF ARCING GROUND FAULTS

Arcing faults are any fault current that flows over a gas or vapor filled gap. For our purpose, this gas is air. The air gap causes a voltage drop that may be considered to have a fixed value for the traditional purposes of power systems analysis. A commonly used value for simplified analysis is 140V. However, the value of the gap voltage has been shown to vary with respect to prospective maximum current, gap length, the permeability of air and di/dt. Various methods have been developed to predict arcing current and voltage for single phase and 3 phase systems more accurately. Most empirical work done to support the models indicates a high degree of variability. The reader is encouraged to look at several of the referenced articles by R.H. Kaufmann & J.C. Page [8], J.R. Dunki-Jacobs[2 & 7], K. Malmedal & P.K. Sen [6], T. Gammon & J Mathews [3, 4 & 5] and H. B. Land [8] on arc current modeling for more detailed analysis than is presented here. For the purposes of the analysis undertaken in this paper our concern is to identify a potential minimum arcing current. The gap is composed of a fixed voltage (anode-cathode drop) that depends somewhat on the degree of confinement of the arc. Within the constraints of a circuit breaker's arc chute, that voltage is typically estimated at 25 volts. Within an unrestrained environment such as inside power distribution equipment it is estimated at 36 volts. The rest of the voltage is dropped in the area in between the anode and cathode and that is the voltage that depends on arcing current and gap length.

The paper "*Arcing Fault Current and the Criteria for Setting Ground Fault Relays in Solidy-Grounded Low Voltage Systems*" [6], by Dr. PK Sen and Keith Malmedal provides a set of simplified equations to model minimum arcing ground currents. Eq. 2 and 3 are derived from that model with the additional allowance of a variable re-strike voltage:

$$i(t) = \frac{V_{LNPeak}}{Z}[\sin(\omega t - \alpha) - A] - B \qquad (2)$$

Where:

$$A = e^{\frac{-R\omega}{X}(t-y)} \sin(y\omega - \alpha)$$

$$B = \frac{E_{ARC}}{R}(1 - e^{\frac{-R\omega}{X}(t-y)})$$

$$\alpha = \arctan(X/R)$$

Z	System Impedance = $(X^2+R^2)^{1/2}$ in ohms
X	System Reactance in ohms
R	System Resistance in ohms
W	System frequency in radians per second = frequency x 2 x Pi
y	time the system takes to reach re-strike voltage from V="0"
E_{arc}	the arc voltage during conduction defined by Eq 3

$$E_{ARC}=36+2.4d+3.2I_{bf} \qquad (3)$$

Where:

d	is the gap the arc must cross
I_{bf}	is the available bolted fault current

Bolted fault current (Ibf), without consideration for closing angle, can be represented by Eq. 4.

$$i_{bf}(t) = \frac{V}{Z}\sin(\omega t - \alpha) \qquad (4)$$

To determine the minimum arcing half-cycle-current Eq. 2 calculation is initiated only after the driving voltage has reached a defined instantaneous re-strike voltage, and is ended when the arc voltage drives the current to zero. During the rest of the half cycle, the arcing current is zero. To derive the minimum possible arcing current the re-strike voltage may be set equal to the maximum peak of the source being considered. For a 480/277V solidly-grounded wye-system the peak voltage line to ground is 391.7 V (277V x √2). For a re-strike voltage equal to the system peak voltage the time to re-strike (y) is ¼ the full cycle period or .00417mS for a 60 Hertz system. A lower re-strike voltage will result in a shorter time before arc re-strike and hence longer lasting arcing current.

This model provides a flat-topped square wave like arc voltage. More sophistical models as presented by Gammon and Matthews [3], in turn derived from work by Stokes, Oppelander and Fisher provide slightly better prediction of arcing voltage and current. However, this model provides for easier analysis and a conservative estimate of minimum arcing current based on a maximum voltage re-strike for several cycles.

The duration of the ½ cycle arcing-current is also affected by the system's impedance's X/R ratio. The arcing ground fault impedance would include phase and ground path impedance. Fig. 6 is the minimum arcing current calculated with Eq. 2, for the following system parameters:

V_{LN}	277V
Z_{fault}	0.0138 Ohms
X/R	4.9 (20%PF)
$V_{re\text{-}strike}$	391V
Arc Gap	32mm (1.25 inches)
Frequency	60Hz

This provides for the following calculated values:

Time to arc initiation (y) – 4.2mS

E_{arc}	177V
I_{bfrms}	20,072A

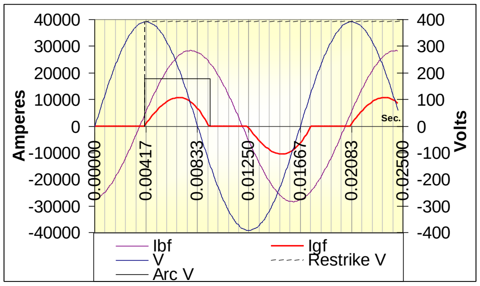

Fig. 6 Minimum Arcing Current Shape

Lowering the arc gap produces a lower arc voltage, a slightly higher peak and a longer arcing current pulse. Changing the X/R ratio towards a more resistive system impedance provides for a shorter arcing current pulse. The function used models minimum arcing ground fault current that may be seen by a ground fault relay or an overcurrent device, especially, in the case where the arcing fault has not become stable. Other models described in the literature provide an estimate of multiple cycles of arcing current under different test conditions. However, a protective device attempting to detect and interrupt a fault as soon as possible should be set to reliably detect the minimum potential fault that can cause significant damage or hazard with some additional sensing margin for assurance. The important conclusion is that, at least at its inception, an arcing current can be intermittent, quite low and non-sinusoidal. Considering the damage it can eventually cause, it may not make it less dangerous but may make it more difficult to detect.

IV. DETECTION AND MEASUREMENT OF ARCING GROUND FAULTS

A. Measurement

Ground faults in most modern circuit breaker trips are measured by performing a sum of the three phase, or three phase and neutral currents, and determining the magnitude of resultant (residual) zero sequence current if present. Ground fault relays in switches often use a single CT through which all conductors are run. The CT will sense the zero sequence flux caused by the net unbalance current within the conductors monitored. Fig. 7 represents a typical residual connection often used in circuit breaker trips.

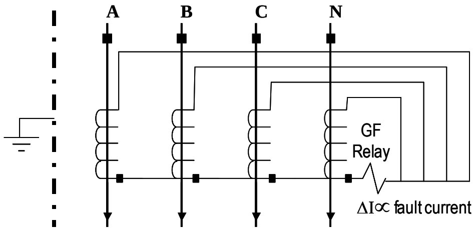

Fig.7 Residual GF Detection Circuit

All devices of modern design are expected to calculate true RMS current for the sensed zero sequence current. The RMS value of the current can be provided by taking each sample, squaring it, adding the samples for ½ period, determining the mean I^2 value and taking its square root. Eq. 5 represents this calculation.

$$\left(I_{RMS}{}^{2}\right) = \frac{\sum_{t_1}^{t_{N/2}} I_{sample}^{2}}{N/2} \qquad (5)$$

Where:

I_{sample} each sample of measured current
N samples per cycle

The calculation in Eq. 5 can be used to determine individual phase currents or a zero-sequence current. Table 1 shows various arcing peak and RMS currents for various combinations of gap, X/R ratio and Re-strike voltage at the same system Z magnitude. Note the range of peak to RMS arcing current as compared to the ratio of 1.41 for a sinusoidal wave. The peak-to-RMS ratios in Table 1 correspond to asymmetrical sine waves with power factors of 35% (1.9) to 50%(1.7) approximately.

Z (Ohms)	Gap mm	Restrike V	X/R	I_{rms}	I_{peak}	I_{peak} / I_{rms}
0.0138	25	375	1	7,223	12,618	1.75
0.0138	25	375	4.9	8,377	14,424	1.72
0.0138	32	375	4.9	7,553	13,028	1.72
0.0138	32	391	4.9	5,858	10,632	1.81
0.0138	32	391	1	5,246	9,845	1.88
0.0138	25	391	1	5,867	10,840	1.85
0.0200	13	391	0.75	5,400	9,766	1.81

Table 1 Asymmetry Table for Various Minimum Arcing Ground Fault Currents

Instantaneous trip circuits may respond to this type of fault current with more sensitivity than to 100% resistive current with equal RMS magnitude similarly to how they respond to the initial peal value of an inductive asymmetrical fault. The exact response to the RMS value is difficult to predict because the wave shape as well as the RMS value of arcing fault current is highly variable depending on many factors.

RMS values calculated by the trip circuits should be accurate as long as the circuit provides a true RMS calculation regardless of non-linearity up to a reasonable level of harmonic content and within the sensing system's dynamic capability. If the ground fault is the only current going through a phase overcurrent and a ground fault sensor, or residual scheme, then both systems should measure the same RMS current and each should respond based on their inverse time tripping characteristics. However, if one or more of the devices is sufficiently sensitive to operate in the instantaneous range the operation may differ from expected due to differences in how the trip mechanism interprets the fault current asymmetry.

B. Arcing, load and overload currents

A GF relay or circuit breaker trip will isolate the fault zero sequence current, subject to some sensing and calculation error, from balanced three phase load currents and neutral current whether they include normal load current, high inrush currents or a 3-phase overload current. However, phase overcurrent devices of all types do not subtract zero sequence currents from their calculations, hence they will measure balanced three phase overloads, load currents and single phase to ground overloads together. The net current sensed by a true RMS phase over-current-protection system will be the sum of all the currents. It is difficult to predict what a phase over-current device will measure with significant certainty. However, it will be more than the fault current by itself.

V. GROUND FAULT PROTECTION AND SELECTIVITY

A. Why is the curve this way?

Ground fault protection has been required in the NEC since 1971. The NEC and other standards have further requirements and definitions regarding ground fault protection at equipment levels. NEMA publication PB2.2-2004 provides the following explanations:

> "GFP devices include current sensing devices (GFS), relaying equipment (GFR), or combination if the current sensing devices and relaying equipment, or other equivalent protective equipment which will operate to cause a disconnecting means to open all ungrounded conductors at predetermined values of current and time. GFP devices are intended only to protect equipment against extensive damage from ground faults."
> "GFP devices are designed for use, primarily, on solidly grounded distribution systems rated up to a maximum of 1000VAC to provide for rapid clearing of ground faults. The National Electrical Code requires ground fault protection in certain instances…"
> "A Class I GFP device is one that does not incorporate means to prevent opening of the disconnecting means at high levels of fault current. It is intended for use with (1) circuit breakers, (2) fused circuit breakers, (3) fused switches having an interrupting rating not less than 12 times their amp rating, or (4) fused switches having an integral means to prevent disconnection at level or fault current exceeding the contact interrupting rating of the switch."
> "A Class II GFP device as defined in the UL 1053, Standard for Ground Fault Sensing and Relaying Equipment is intended for use with disconnect of limited interrupting rating and incorporate means to prevent opening of the disconnecting means at excessive levels of fault current."

NEC and UL 1053 define various pick up levels and timing for ground fault protection. Circuit breaker ground fault functions and ground fault relays used in low voltage systems follow these guidelines. The following values are listed in the NEC or UL 1053. Fig 8 shows these levels on a time-current-curve along with a typical circuit breaker's ground fault function with I^2T included:

> NEC, Article 230: Maximum Pick up level for the GFP used at service entrance conductors is 1200A
> NEC, Article 230: Maximum clearing time at 3000A amperes shall be 1 second.
> UL 1053: Maximum clearing time at 150% of nominal setting shall be 2 seconds.

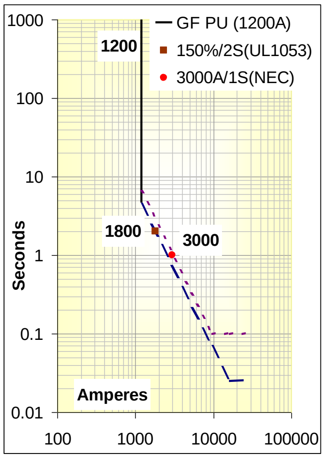

Fig. 8 Ground Fault Protection – Mandated Parameters

Fig. 9 is a time current curve for various ground fault protective devices available in the industry. All the curves shown include an I^2T characteristic. The NEC mandated 1 second clearing at 3000A is also included. Though the actual pickup settings vary slightly from device to device the general shape and location is similar, as all the devices must meet the same standard.

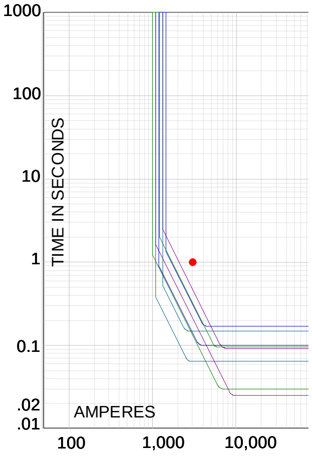

Fig 9 Ground Fault Protective Device Curves

Guidelines for maximum acceptable damage are offered in NEMA publication PB 2.2-2004, *"Application Guide For Ground Fault Devices For Equipment"* [1]. These guidelines are provided by NEMA in an attempt at providing a method by which to select acceptable protection while still achieving selectivity using pick-up settings and time delays. The damage curves are a suggested compromise between damage and system reliability. The NEMA standard suggests an acceptable level of damage caused by an arcing ground fault that still allows for reasonable selectivity as 250 times the current rating of the over current protective device protecting the circuit. If the device is rated the same as the conductor then the limit is 250 times the rating of the conductor in amperes squared seconds. The function to determine damaging energy provided in the NEMA standard is defined in Eq. 6. Eq. 7 is derived from Eq. 6 and provides the relationship of time to current for the specified level of damage for respective conductor sizes

$$\text{Acceptable Damage} = 250I_r = K(I_r)^{1.5}t \qquad (6)$$

$$I_s = (250I_r/(t+t'))^{2/3} \qquad (7)$$

Where:

I_s	the current setting of the short time delay or instantaneous trip device, in amperes.
I_r	the rating of the disconnect device, or the current setting of its long time trip, in amperes.
t	the operating time of the GFP device, in seconds
t'	the operating time of the disconnect, in seconds
K	1.52×10^6 for CU, 0.72×10^6 for AL

Fig. 10 is a time-current-curve showing the standard mandated GF points and the suggested maximum acceptable damage curves for various size conductors. The difference in slope is caused by the damage curves having a slope of $I^{1.5} \times t$ = a constant, versus the typical GFP function having a slope of I^2T equals a constant. For a 1200A conductor a GF function set at 1200A with a 100mS time delay provides an acceptable operating time up to about 15,000-20,000A based on the devices actual operating time. Using a faster time delay of about 25mS (1.5 cycles) extends the adequate level of protection to about 50,000A.

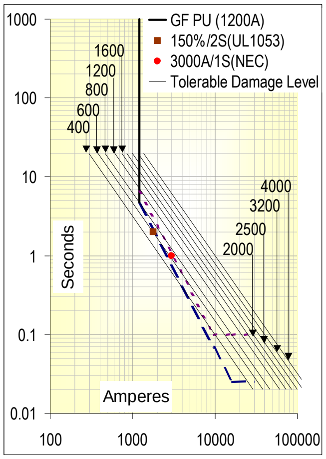

Fig. 10 Suggested Maximum Allowable Damage Curves From NEMA PB 2.2

Fig. 11 shows a 4000A adjustable circuit breaker with I^2t off and on, along with a 1200A ground fault protection curve with I^2t on (GF I^2t off is not shown). The curve also includes the NEC defined ground fault protection limits and the suggested acceptable damage curve for 1200A and

4000A buses. The ground fault protection function provides better protection than a 1200A or 4000A circuit breaker over a broader range of fault values even when the circuit breaker is set up at minimal pick up levels and delays. Most circuit breakers would be set somewhat higher and possibly slower to achieve some measure of coordination.

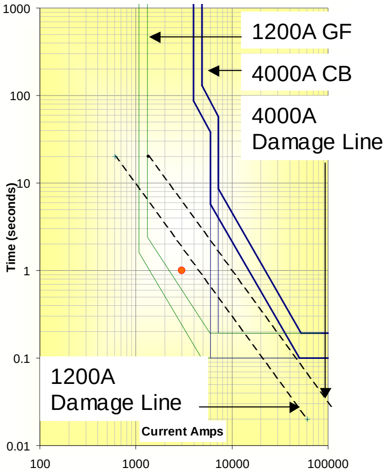

Fig. 11 NEMA Suggested Damage Limits Compares to 1200A GF Curve and 4000A CB Curve

B. *Selectivity limitations*

For a power distribution system that incorporates some ground fault protection to be fully selective proper coordination must be achieved between phase and ground fault protection on all devices. Coordinating phase protection and ground fault protection separately may not n provide full system selectivity. The devices operating on the load side of the GFP must be completely selective with the GFP above them and the difference in pick up levels should account for the possibility the downstream phase-protectors may include load phase current in addition to the fault current in its sensing system, while the GFP will only incorporate the zero-sequence fault current.

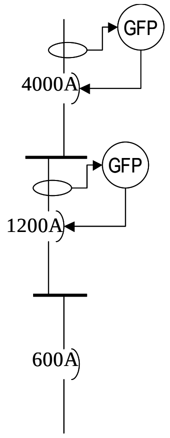

Fig. 12

Fig. 12 shows a simple 3 circuit breaker one-line diagram with the two upstream devices including a ground fault function. The third device, sized at 50% of the second device, does not include a ground fault function. Fig. 13 shows time current curves for the 5 protective functions. The time-current-curve in Fig. 13 shows that the two line-devices can be made selective with respect to each other for phase protection and ground fault protection. However, the 600A phase protector is not selective with either of the two ground fault relays even though all its settings are set at, a marginally useful, minimum. The ground fault functions are set at 1200A and 576A respectively. Removing the I^2T slope on the GF function would allow the lower GF setting to be 944A. However, overall selectivity is not improved unless the third overcurent phase protector's rating is significantly decreased as shown in Fig 14.

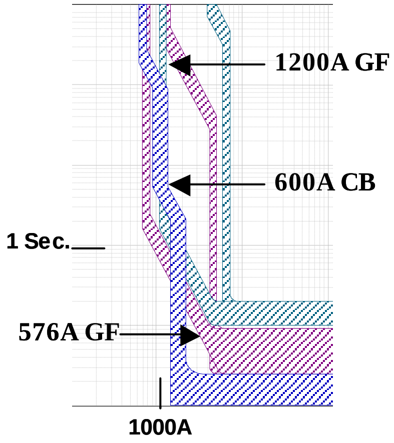

Fig. 13 TCC For Devices in Fig 12

Fig 14 shows a definite time GF setting of 1200 and one at 944A. The largest molded case CB of this type that can be said to be selective is included in the time current-curve. The molded case CB is rated 225A and is set with all it settings at minimum which could significantly impair its ability to be selective with any devices further downstream, or sustain normal transient load requirements.

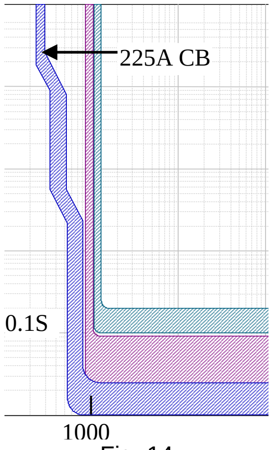

Fig. 14

Fig. 15 shows a 225A RK5 fuse plotted along with the same two line-side GF devices as fig 11. Because of the shape of the fuse curve, it is somewhat more difficult to coordinate with the ground fault functions than an adjustable circuit breaker. However, the exact coordination will depend on the specific devices used. The shape of the ground fault curve will vary between devices but variation is limited due to the requirements imposed by standards.

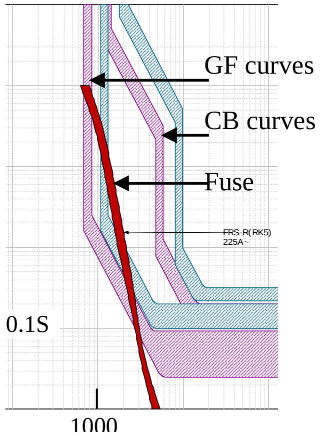

Fig. 15 RK5 fuse and GF Functions

Another way to approach device selection is by selecting the branch device below the last ground fault protective function for which the designer wishes to optimize selectivity. The most common overcurrent circuit breaker in many 480/277V systems is the 20A single-pole circuit breaker. Since this circuit size is common and many loads may be connected to each circuit, ground faults below it may be an in issue. To a single-pole circuit breaker, ground faults, phase faults and overloads look alike. From the symmetrical component perspective, a phase to ground, phase to neutral or phase to phase fault is the same. So, if the designer wishes to provide ground fault protection for circuits above single pole circuit breakers it is important to know what is the lowest ground fault setting that maintains selectivity. Fig. 16 shows a nominal 240A ground fault setting above a 20A lighting circuit breaker that provides selectivity. The exact values will vary by device type and manufacturer. However, most such devices will have similar limitations. A 240A ground fault function is typically associated with a 400 or 600A circuit breaker. The value of the GF limits the minimum size of the circuit on which it can be implemented. This limitation can impact the size of panels and overall design of the system.

Article 517 of the NEC requires that the main circuit breaker in the normal distribution system of a hospital does not trip for a ground fault in the distribution circuits fed by the main. The normal way for designers to fulfill this requirement is to include two levels of ground fault protection. However, this may not always be required. If the feeder circuit on the main bus is sufficiently small, it will not require ground fault protection. Adding ground fault protection to too small a panel feeder may lower system reliability as it will cause the panel main to trip for faults that would otherwise be selectively handled by the branch circuit breaker.

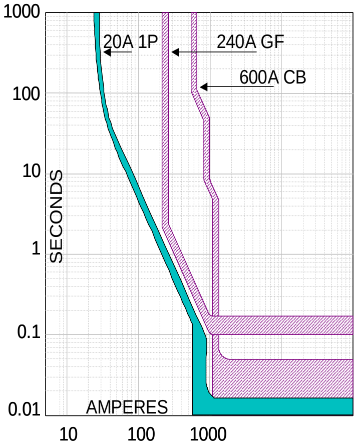

Fig. 16 20A 1 Pole Circuit Breaker Under 240A GF

When considering how the various overcurrent devices will operate relative to a ground fault current we can also add considerations for the various potential idiosyncrasies of the single phase to ground arcing fault downstream of the third overcurrent protective device.

1) Any of the devices may have additional load current in addition to the arcing fault current. This makes the device more sensitive and hence shifts it to the left in the time current curve with respect to fault current.
2) The arcing fault is non-linear and hence has a peak that is larger than 1.41 times the RMS value so the instantaneous trip of some circuit breakers may be more sensitive to the arcing fault than the RMS value of that arcing fault would indicate.

C. Alternative Curve Shapes

Slightly better selectivity may be achieved by using alternative shapes for the ground fault curves. The time-current-curve in Fig. 17 shows one such shape. Using a steeper fuse like ground fault characteristic and a lower long-time band on the feeder circuit breaker below the 1200A ground fault function allows an 800A circuit breaker to be made selective under the 1200A ground fault function. Not shown is the effect of zone selective interlocking which would allow the various time bands to overlap while maintaining selective protection.

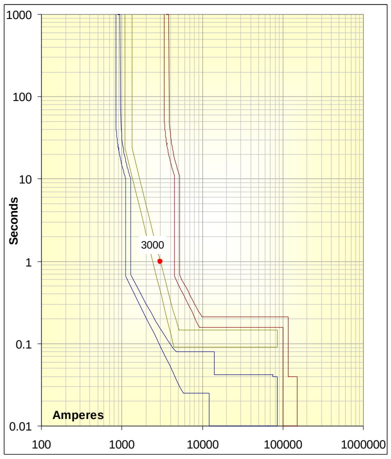

Fig. 17 Alternative GF Curve Example

VI. SUMARY

A review of industry literature and standards demonstrates that arc ground faults are sufficiently frequent and serious in low voltage power distributions systems to merit special consideration in system design and standards. Dedicated sensing, dedicated protection and dedicated algorithms are used to provide additional protection against low-level arcing ground-faults. A review of the literature on arcing faults demonstrates that they are difficult to characterize because of the many factors that affect them, however relatively low values are possible, particularly in the initiating cycles of fault current. In addition, even though arc impedance is resistive, an arcing fault's waveform may have a peak to RMS ratio greater than that of a symmetrical-waveform providing for differences in how different protective devices may sense the fault in the instantaneous range. Time current curves that are plotted in symmetrical amperes do not fully communicate how the protective devices may function under low arc fault conditions in the instantaneous range. This non-linearity in the fault current may make overcurrent device behavior difficult to predict if interruption is expected at instantaneous or near instantaneous speeds. Because of the frequency of arcing ground faults coordinating ground fault protection is particularly important and should not be ignored, however, the characteristic shape of ground fault curves makes coordination of ground fault protection with downstream protection particularly difficult.

VII. CONCLUSION

Assuring optimal system protection and system reliability is an inexact science due to the unpredictability of fault currents. However, qualified engineers can take into account an understanding of how the various protective devices function and what the more probable, more dangerous and most difficult to sense faults may be while designing systems and selecting protective devices that provide an acceptable compromise between protection and coordination. Traditional time current curves may not tell the entire story at a glance, understanding the effect on trip mechanism of potential peak currents and RMS currents may be required.

In a system, where selective tripping is desired under all conditions, and ground fault protection is used, phase and ground fault protection must be coordinated together. This places significant restrictions on the size of the devices below the layer of protective device that have dedicated ground fault sensing and protection per code requirements. Some devices may provide more capability than others based on the specific needs of the application. Both fuses and circuit breakers each have their disadvantages and advantages. Optimally selecting protective devices and their settings may not be as simple as looking for non-overlapping curves, or following a table.

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IX. VITA

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