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Protection Application Which Achieves Fast Tripping Times for Bus Faults and Faults Close to a Bus to Reduce the Hazard Risk of Arc Flashing

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Presented to the

34th Annual Western Protective Relay Conference
October 16-18, 2007
Spokane Convention Center

2nd edition

Protection Application Which Achieves Fast Tripping Times for Bus Faults and Faults Close to a Bus to Reduce the Hazard Risk of Arc Flashing

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Arc flashing in electrical equipment and the potential hazard it creates to humans is a serious concern and the Occupational Safety and Health Administration (OSHA) has given this topic much attention. The NFPA (**N**ational **F**ire **P**rotection **A**ssociation) issued the standard 70E and the IEEE issued IEEE Standard 1584 which also addresses arc flash hazard. The hazardous risk categories defined in these standards are based on the energy level released during the arc flash. The main factors determining the arc flash energy are the short circuit current, the distance from the electrodes and the duration of the arc flash. Utilities are using different approaches to reduce the arc flash energy. The protection engineer can contribute to these efforts by developing solutions with fast tripping protection schemes.

This paper will give an introduction to the problematic phenomena of arc flashing. For protection engineers important terms and facts in the NFPA 70E standard and the IEEE 1584 standard will be presented. The importance of the fault clearing time will be discussed in detail. Protection engineers can offer a positive contribution by reducing the fault clearing time to reduce the hazard caused by arc flashing.

Protection schemes which achieve fast fault clearing times for bus faults and feeder faults will be reviewed. The different technical solutions will be evaluated against economical considerations. The reverse interlocking scheme is often used on medium voltage distribution busses and industrial busses as a compromise between economical and performance considerations and usually achieves a reasonable clearing time for all faults on the bus. In this paper an application will be introduced which is based on the reverse interlocking scheme additionally it offers a new solution that achieves a fast fault clearing time for bus faults and close in faults. This is normally the area within a substation, where arc flashing can cause a potential hazard for operators. This application will eliminate the problem of longer fault clearing times for faults close to the bus due to the co-ordination with radial feeders relays. This paper will discuss the necessary settings considerations and will show the limits of this application.

Test results will demonstrate the advantage of this application. The biggest obstacle in applying protection schemes such as the reverse interlocking and the new solution presented in this paper is the additional wiring between the relays. For this reason the paper will show a new approach and a modern solution of relay to relay communication which eliminates this obstacle.

1.0 Basics

In the National Fire Protection Association's (NFPA) 70E standard, issued in 2004 we can read "Live parts to which an employee might be exposed shall be put into an electrically safe work condition before an employee works on or near them, unless the employer can demonstrate that deenergizing introduced additional or increased hazard or if infeasible due to equipment design or operational limitation"

If working close to energized parts cannot be avoid a "Flash Hazard Analysis" must be done in order to determine the "Flash Protection Boundary". The Flash Protection Boundary defines the distance to a possible arc in which a person will endure second degree burns. Up to this distance an employee is only required to wear none melting, flammable material with a fabric weight at least 4.5 oz/yd^2. It is assumed, that the incident energy level will be 1.2 cal/cm^2 up to 1.5 cal/cm^2 depending on the fault clearing time.

If work has to be done inside the Flash Protection Boundary the incident energy level has to be determined and appropriate personal protection clothing has to be used.

[Source: NFPA 70E from 2004 Table 130.7(C)(11)]

Hazard/Risk Category	**Clothing Description**	**Incident energy [cal/cm^2]**
0	non melting, flammable material with a fabric weight at least 4.5 oz/yd^2	1.2 (1.5 for t<0.1 s)
1	Flame retardant (FR) shirt and (FR) pants	5
2	Cotton underwear, (FR) shirt and (FR) pants	8
3	Cotton underwear, (FR) shirt and (FR) pants Plus two FR coveralls	25
4	Cotton underwear, (FR) shirt and (FR) pants Plus multilayer flash suit (3 or more)	40

The standards NFPA 70E describes several formulas for different voltage levels and for different situations to calculate the incident energy produced by an arc. This paper will focus on applications greater as 600V and the following formula is given in NFPA 70E to calculate the incident energy in cal/cm^2:

$$E = \frac{793 \cdot F \cdot V \cdot t_A}{D^2}$$

Where:

- E: incident energy, cal/cm^2
- F: bolted fault short ciruit current, kA
- V: system phase-to-phase voltage, kV
- tA: arc duration, seconds
- D: distance from the arc source, inches

As protection engineers we only have influence on the fault clearing time (arc duration) and in some cases on the distance to the arc. The system voltage is normally a known quanity. The bolted fault short circuit current can be influenced by the primary system design. The grounding method of the network can have a significant influence on the fault circuit current. If the system is isolated or compensated the fault current can be reduced to under 100A. Resistive grounded networks also have the goal to reduce the fault current to a certain level.

2.0 Fast fault clearing solutions

2.1 Using different setting groups

Modern numerical relays normally offer several setting groups which can be activated at any time. Where work has been scheduled under energized conditions the sensitivity of protection elements could be increased and the normal coordination could be deactivated in favor of the higher protection for the employees against an arc flash hazard, by just selecting a different setting group with more sensitive setting. The goal would be to archive instantaneous tripping for the case of an arc fault. After the work is finished the original settings which were coordinated with all other relays would be reactivated.

A disadvantage would be that the co-ordination is not effective. Any fault inside of the grid during the time of the work could cause unselective tripping. In addition, there is a certain risk that after the work is finished the correct setting group is not activated again!

2.2 Normal reverse interlocking scheme

The reverse interlock scheme provides an instantaneous tripping bus protection for substations with radial feeders. This scheme will archive instantaneous tripping for all bus faults without losing the coordination to the feeder relays and would be always active without switching setting groups. However if the work has to be done close to the energized feeders, this scheme will not reduce the fault clearing time for feeder faults. This will be discussed later and solved by the advanced reverse interlocking scheme. The scheme utilized the existing overcurrent relays, used to protect the feeders and the incoming source feeder including the transformer. The pick up of any of the feeder relays is used to block the instantaneous overcurrent element on the source feeder (fault location 2 in diagram 1). For a bus fault (fault location 2 in diagram 1), none of the feeder relays will pick up and the instantaneous overcurrent element on the source will trip instantaneous for any bus and transformer fault. The instantaneous element needs to be time delayed by approx. 30- 50ms to make sure that a blocking signal generated from the pick up of a feeder relay is securely detected.

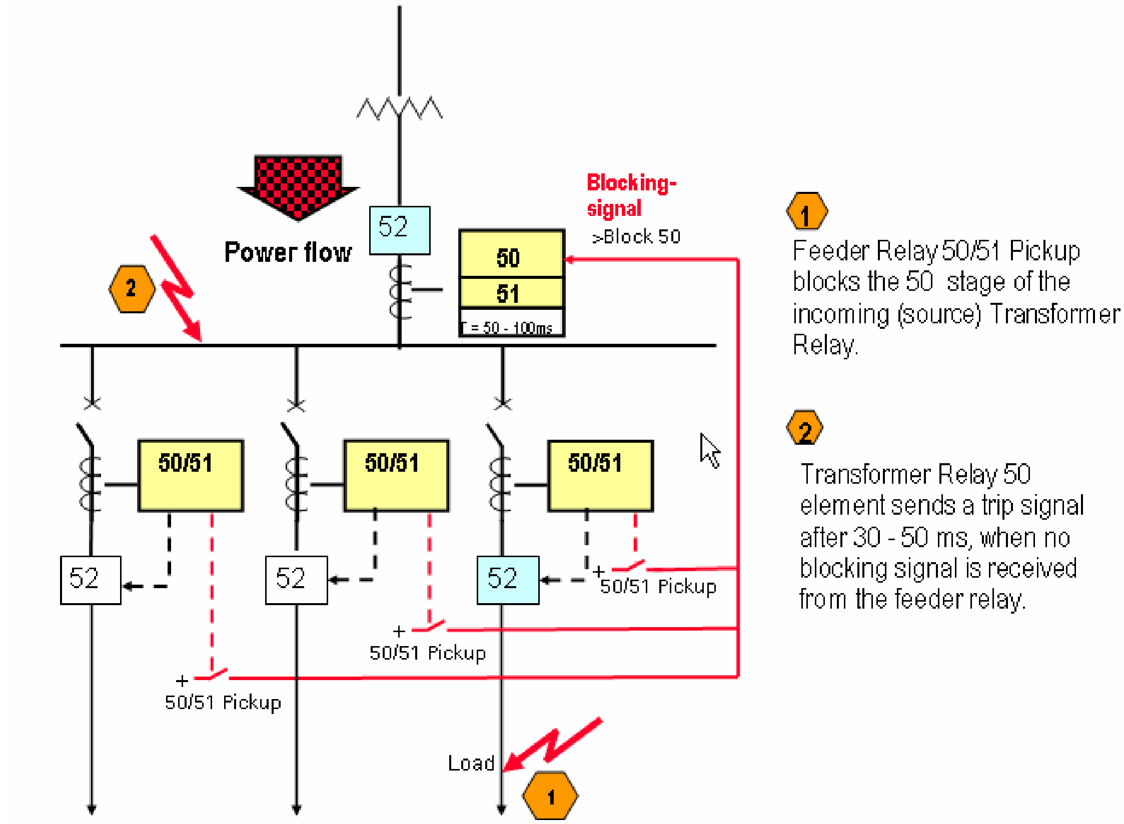

Diagram 1: Principle of a Reverse Interlocking Scheme

The expense of separate bus differential relay systems can be eliminated. The reverse interlocking scheme is economical to use because the cost of the functions are already incorporated into the existing overcurrent relays. The scheme requires only one additional instantaneous element (50) on the source feeder. Normally only an inverse overcurrent element (51) is used and coordinated with the feeder relays which results in time delayed fault clearing and more critical arc energy for bus and transformer faults. In the reverse interlocking scheme the 51 element can still be used independent of the 50 element, but it has only a back up function.

In the past, the wiring between all the relays was a serious obstacle in applying this scheme. However with the introduction of modern communication protocols such as IEC61850, which allow manufacturer independent relay to relay peer communication, the wiring can be replaced by sending the pick up information of the feeder relays via communication (GOOSE message) to the transformer feeder relay. The solution utilizing IEC61850 communication also has advantages in relation to security and speed versus the hard wired version. In IEC61850 the GOOSE messages can be monitored that makes it possible to detect a “broken connection” instantaneously and normally before it can cause any unselective operation! Tests between the timing behaviors of a GOOSE message versus a wired solution have shown that the GOOSE message was always a few milliseconds faster than the wired solution [1].

The scheme can only be applied on applications where the fault clearing time is allowed to be 8 -10 cycles or greater for bus faults. The 8-10 cycles restraint results from the sum of the relay pick up time of approx. 2 cycles, the time delay of the 50 element on the source of 2-3 cycles and the circuit breaker operating time of 3- 5 cycles. If faster tripping is required a real bus differential relay needs to be used.

Another limitation is that the above introduced reverse interlocking scheme can only be applied if the radial feeders are only load feeders. If any of the feeders have also generation connected, a directional overcurrent relay (67) must be used on all feeders with generation.

2.3 Reverse interlocking scheme with several infeeds

Bus systems with several infeed feeders are not uncommon and more likely at higher voltage levels. Even in distribution and industrial applications, the so called main-tie-main application can be considered as a bus (actually two busses) with at least two infeeds. This is because the tie bus connection can be used as load as well as source.

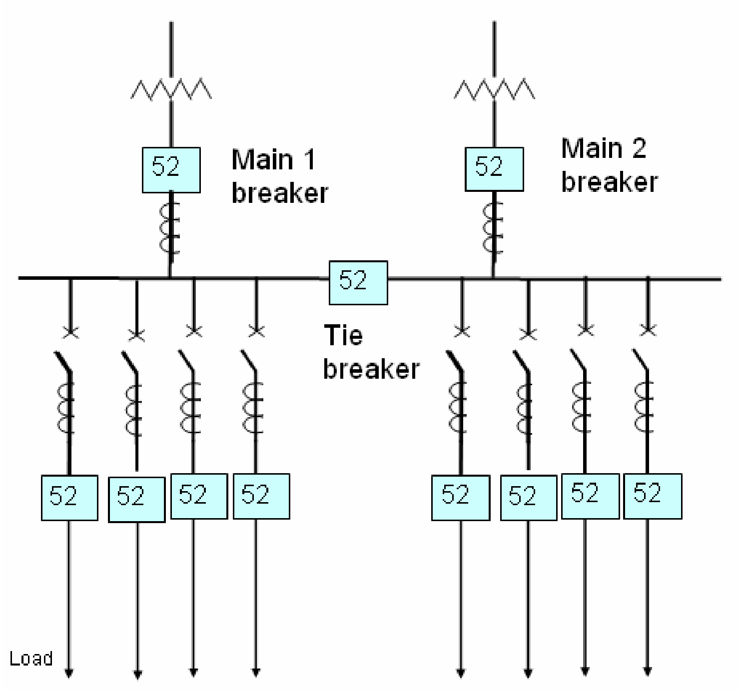

Diagram 2: Main-tie-main configuration

The reverse interlocking scheme can also be applied here, but on all feeders with infeed a 67 element is required. The blocking signal used to block the trip on all infeed feeders gets build by the 50/51 pick up of any load feeder relays and/or of the pick up of the directional overcurrent relays on the generation feeder if the detect a fault not in the direction of the bus. Whenever a relay on the generation feeder detects a fault towards the bus and doesn’t get a block signal from one of the other relays, it will trip with an appropriate time delay of 30-50ms.

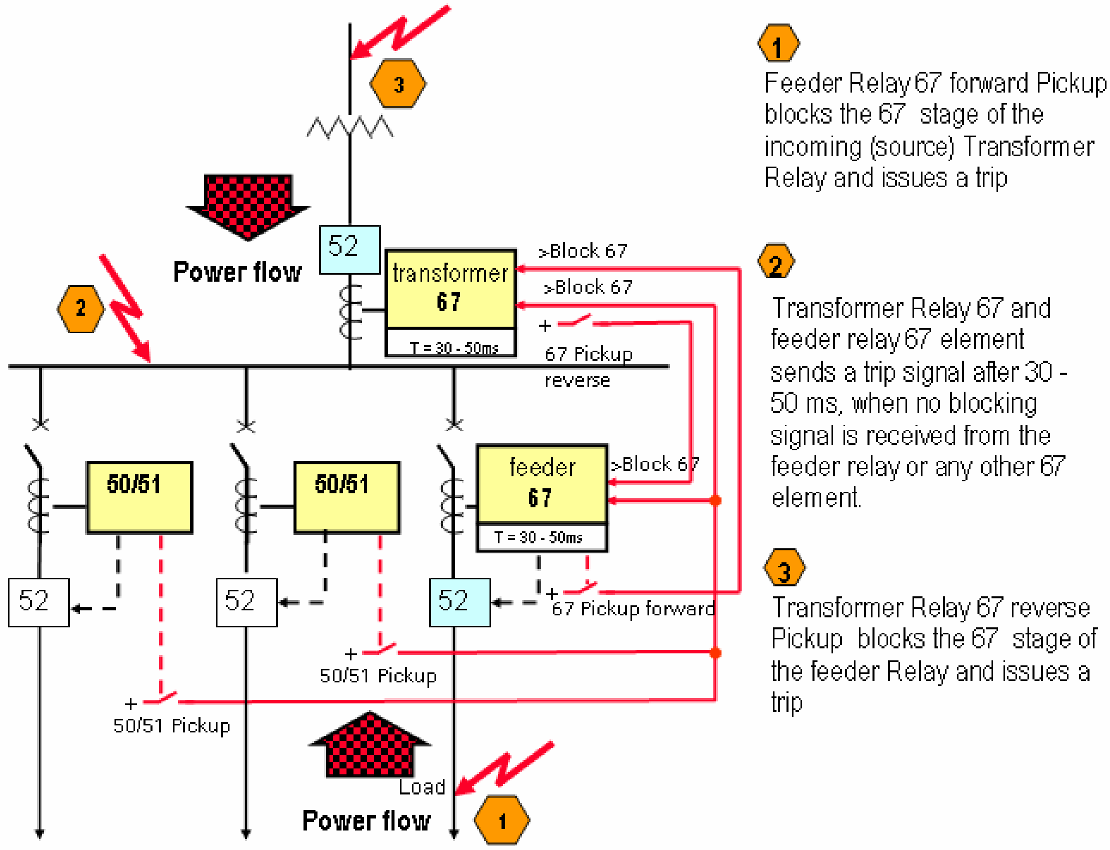

Diagram 3: Reverse interlocking scheme with several infeeds

The scheme will also offer an effective and economical way to archive a fast bus protection. However, the scheme requires 67 protection elements and needs potential transformer measurements from the bus voltage for this purpose. In addition the wiring between the relays is now more complex as in the simple reverse interlocking scheme. The last mentioned disadvantage will also disappear with the use of IEC61850 inter relay communication.

The sensitivity of the settings has to be coordinated with the different infeed conditions and in some cases it will result in a sequential tripping of a bus fault. The requirements on fault clearing time for a bus fault will define whether the reverse interlocking scheme can be applied!

Both schemes, the reverse interlocking scheme with one source and the reverse interlocking scheme with several sources will be able to archive a fast tripping time for bus faults only. A real bus differential protection scheme 87 can also clear bus faults instantaneous but requires additional CT wiring. By doing so the fault duration is minimized and the arc flash energy is reduced without compromising the security and the reliability of the protection. However, if the fault is right behind the feeder CT none of the above mentioned bus protection schemes will clear the fault. In this case the inverse over current relay (51) will in coordination with the downstream relays clear the fault with an appropriate time delay. Unfortunately the 51 relay close to the bus is the last relay what will allow to trip for a feeder fault and therefore tripping times of seconds are not untypical for these faults. In many cases faults behind the CT are still inside the substation area and they will create a certain arc flash hazard potential for people inside this area. This problem is addressed in the advance reverse interlocking scheme presented here in this paper.

2.4 Advanced Reverse Interlocking scheme

The goal of the advance reverse interlocking scheme is to reduce the tripping time for arc faults on the buss and for arc faults on feeder locations close to the bus. By reducing the tripping time the incident energy will be reduced. To explain the principal of the advanced reverse interlocking scheme the simple reverse interlocking scheme with only one infeed will be used and modified. The principal can also be applied to schemes with several infeeds. The idea of the advanced reverse interlocking scheme is to use the zone information of a distance element 21 to detect faults close to a bus. The instantaneous overccurent element 50 on the source of the simple reverse interlocking scheme becomes replace by a distance function 21. In relation to bus faults nothing will change.

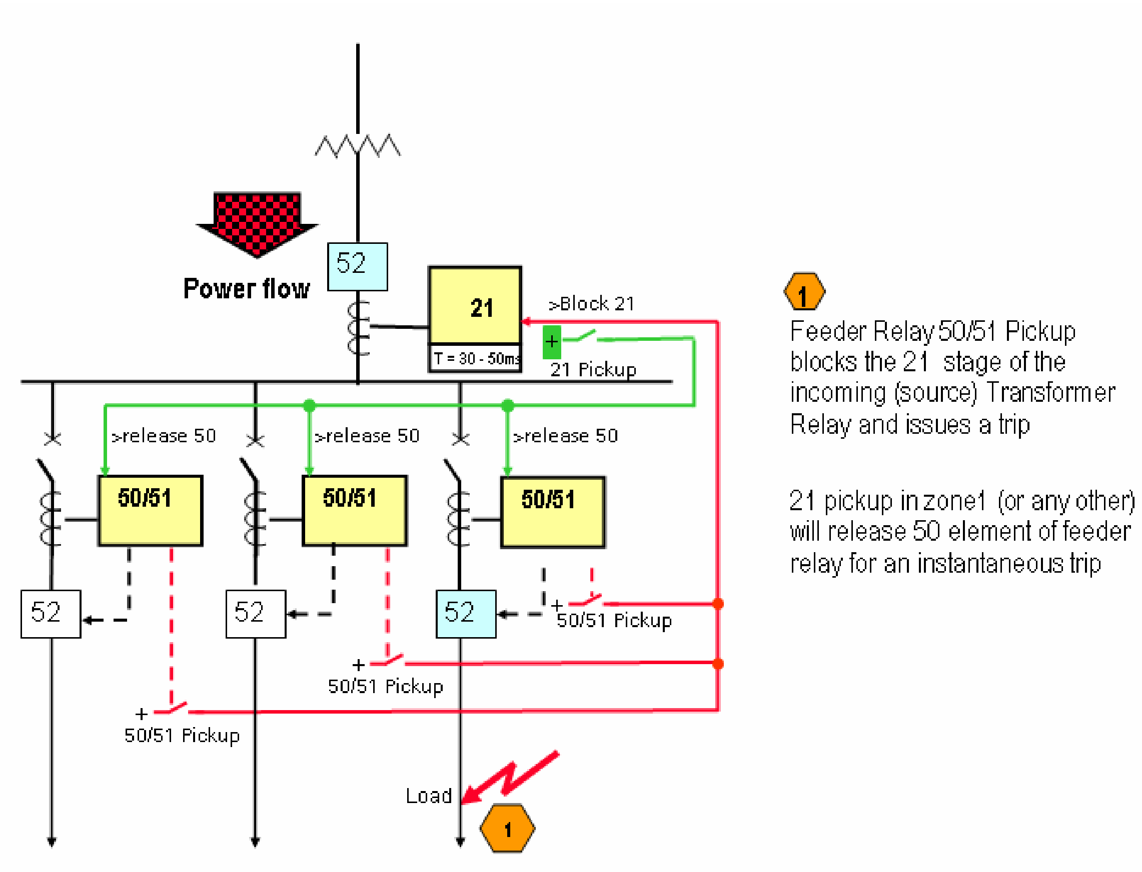

Diagram 4: Reverse interlocking scheme with several infeeds

In an event of a bus fault, none of the feeder relays will pick up and the distance element is allowed to operate instantaneously after an appropriate time delay. Time delays of 30-

50ms are used just to make sure that any pick up of a feeder relay can be detected in time.

A fault of on a feeder can be handled more intelligently by the advanced reverse interlocking scheme. The inverse overcurrent element 51 in the feeder relay picks up and then starts the timer and blocks the tripping of the distance element on the source. At the same time the distance element will determine whether the fault is close to the bus by measuring the fault impedance inside of zone 1 (or any other zone). This information is than passed back to the feeder relays and can be used to release an instantaneous overcurrent element 50 to clear the fault without time delay!

This above mentioned advantage must be compared against the higher cost of a distance relay compared to a simple overcurrent relay and the additional installation of potential transformers on the bus. In the past the extensive wiring between the relays was not permitted by many users. For this scheme, the pick up information from the feeder relays are sent to the distance relays and the pick up of the distance relays has to be sent to each of the feeder relays. A modern protocol, like IEC 61850 which allows manufacturer independent relay to relay communication, has eliminated the extensive wiring problem. An Ethernet based station bus will connect all relays and makes it possible to exchange all information between the relays via GOOSE messages.

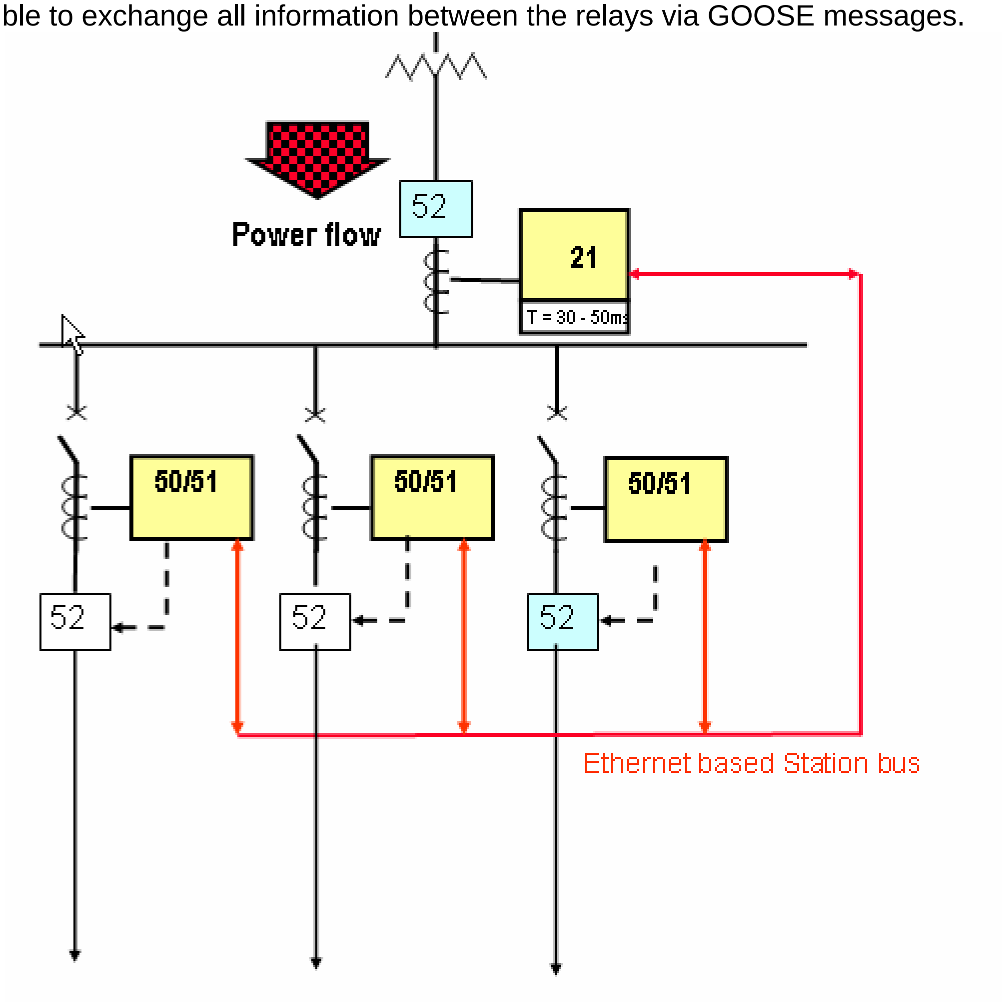

Diagram 5: IEC61850 Station bus

If the line/cable length is not long enough that a distance relay can securely determine whether the fault is on the line or behind the next bus section the scheme cannot or only partly be used. Modern numerical distance relays provide reliability and are able to securely protect lines or cables of a secondary impedance of 0.01 Ohm (based on 5A nominal current) which are sometimes less than a mile!

If only one distance zone is used, the reach of the zone element is normally set such that it will detect faults up to 60% - 80% of the shortest line connected to the bus. Based on the load in the unfaulted feeders, the impedance between the relay and the fault location will be measured to small. This can lead to an overreach and therefore attention has to be paid to the maximum load conditions. An other approach can be, to set only the minimum impedance possible to set in the relay of 0.01 Ohm (secondary) what represent a line distance of approx. 500 feed. By doing so, at leased all faults inside the substation or the gear can archive instantaneous tripping time.

If the lines or cables connected to the bus are extremely different in length, several distance zones can be used and each zone can be assigned to a certain feeder (see diagram 5). This would best utilize the use of the distance element. Modern numerical distance relays usually offer 5 or more zones.

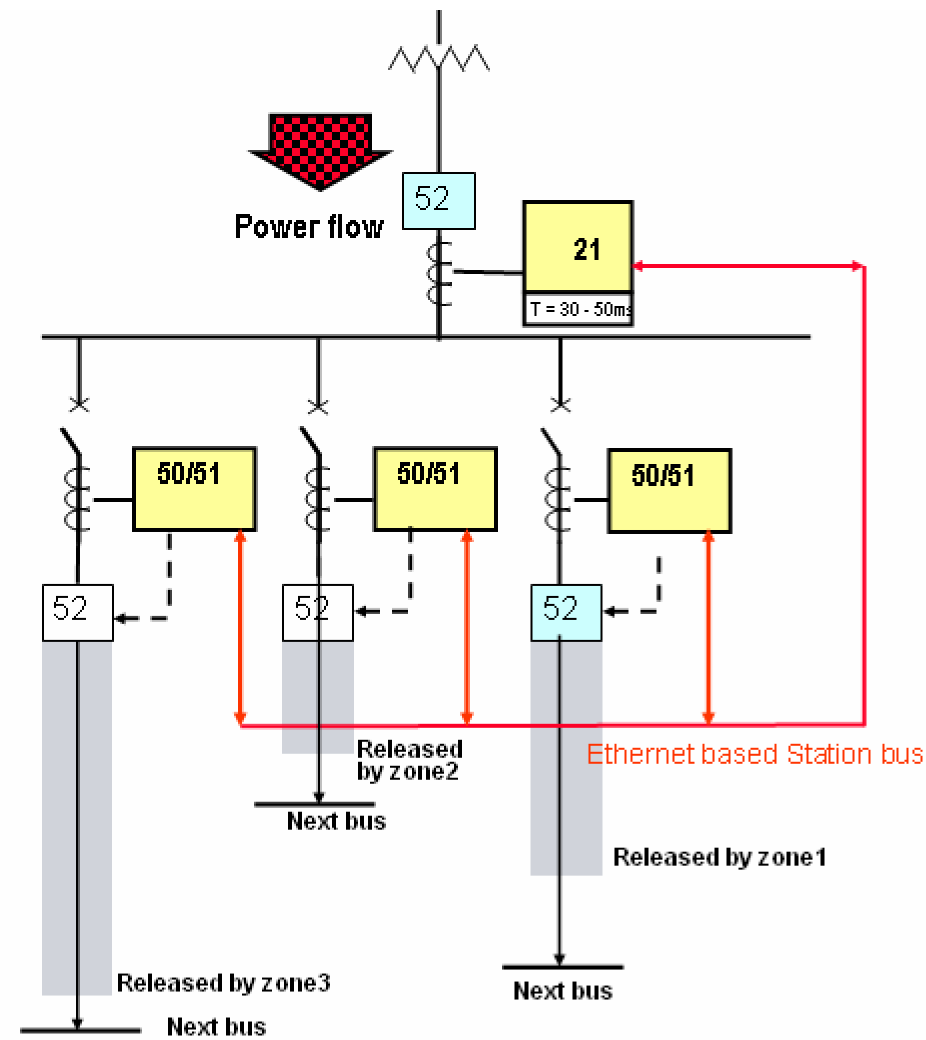

Diagram 6: Advance reverse interlocking scheme with several distance zones

The advanced reverse interlocking scheme archives fast tripping time for all bus faults, and for faults close in to the bus. By doing so the power quality to loads off the bus are significantly improved and the risk to upstream transformer damage due to the long clearing time is also reduced. At the same time, the arc flash incident energy is reduced; this will provide safety by protecting people close to the fault location.

3.0 Breaker control from a safe location, either, local or remote

The NFPA 70E standard also applies to local breaker control. If the location of the breaker control is inside the Flash Protection Boundary the person who wants to control the breaker is required to wear personal protection clothes in relation to the incident energy level. Modern numerical protection relays with communication ability offer a solution where the actual control is done not inside the Flash Protection Boundary but from a remote location.

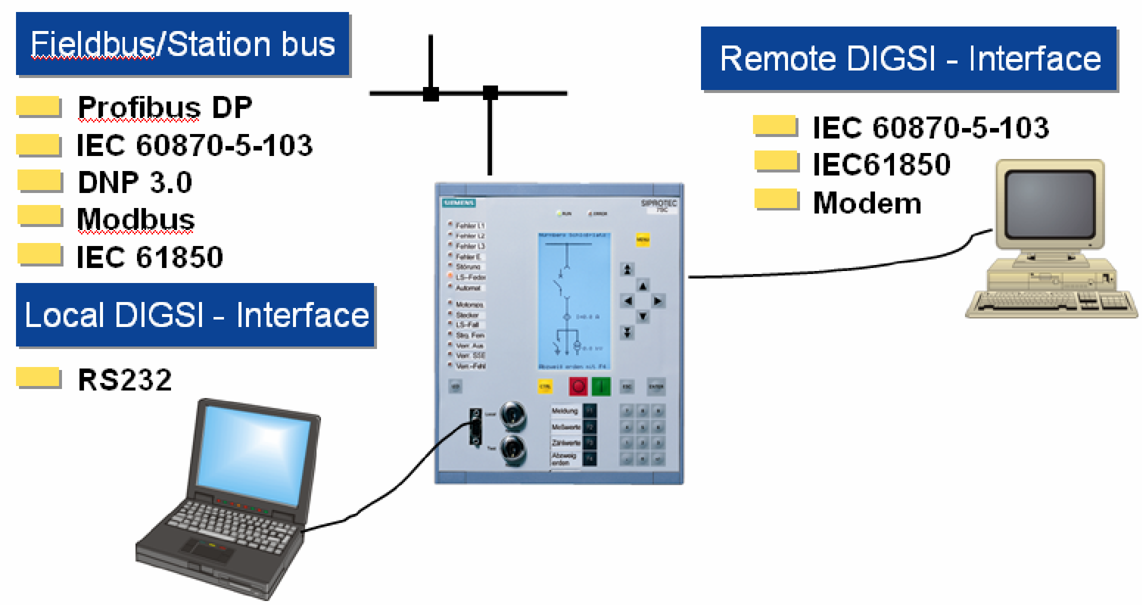

Diagram7: Breaker, local or remote control

In addition all the interlocking conditions can be supervised from the relay which leads to a more secure operation. For example, the blocking of a close command when the ground switch is closed.

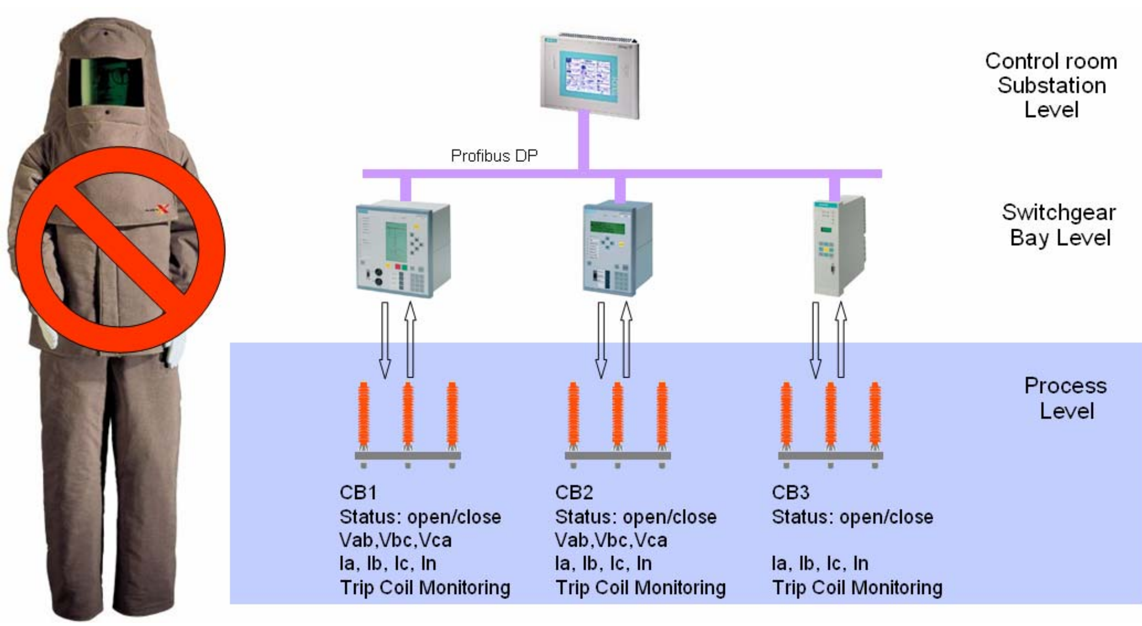

Diagram 8: Example of a local control solution

Predefined solutions allow for the replacement of existing electromechanical or static relays without communication abilities, with modern numerical relays with a minimum of work. The system shown in diagram uses Profibus DP for the communications between a local control display located in a secure location inside the substation.

4.0 Conclusion

Arc flash hazard is a serious danger for all personal which have to work close proximity to energized parts. Occupational Safety and Health Administration (OSHA) has given this topic much attention. The NFPA (**N**ational **F**ire **P**rotection **A**ssociation) issued the standard 70E and the IEEE issued IEEE Standard 1584 which also focuses on arc flash hazard. From the protection point of view, fast tripping schemes can contribute and will reduce the incident energy. In this paper an advanced reverse interlocking scheme was introduced, which can achieve a fast fault clearing time for faults on the bus and for faults close to the bus. This scheme enhances the reliability and security of the protection for bus applications. By utilizing the new standard IEC 61850 and its ability of manufacture independent, relay to relay communication, most of the disadvantages of the presented scheme can be eliminated.

In addition a solution was presented which uses the communication ability of modern numerical relays to perform safe local as well as remote operations outside of the Flash Protection Boundary.

5.0 References

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6.0 Biography

Dr. Juergen Holbach is manager of operation at Siemens Power and Distribution in Wendell North Carolina. He was born in Germany and graduated from the University of Berlin with a PhD in Electrical Engineering. He joined the Siemens AG in 1992 as a development engineer in Berlin Germany. In 1994 he moved to the product management group for protection relays in Nuremberg Germany. In 2000 he joined Siemens Power Transmission and Distribution in Wendell, NC as a product manager for transmission relays.