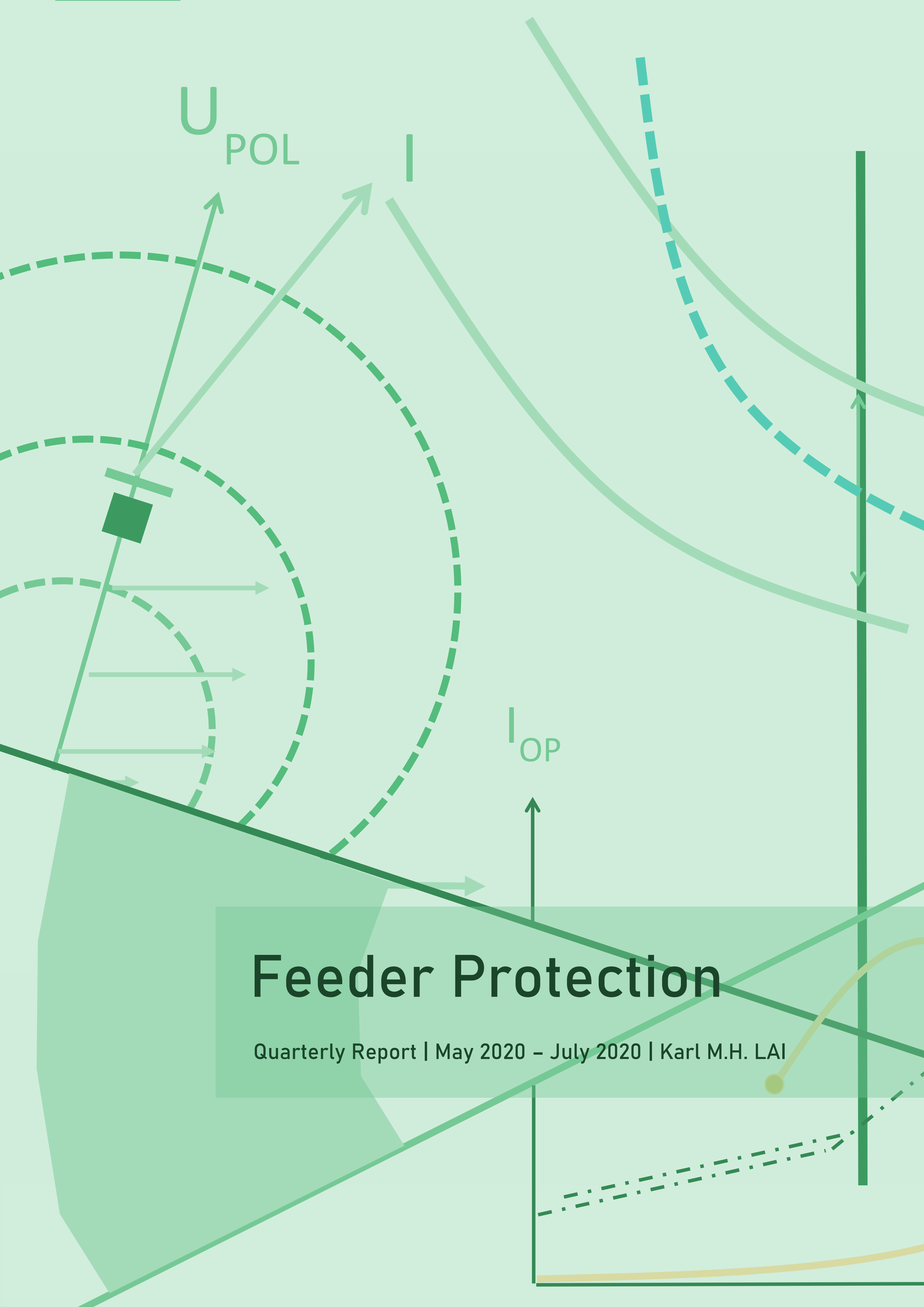


Feeder Protection

Quarterly Report | May 2020 – July 2020 | Karl M.H. LAI

Introduction

Power system requires a protection to <u>detect and isolate faults selectively at a predesigned time</u> to maintain reliability and stability. Feeders, as the most vulnerable and interruptible elements in the network, should be well protected to avoid tripping upstream and isolating loads. This report discusses the major operating principles in feeder protection, including **(directional) overcurrent**, **differential** and **distance**, their additional features in relays and considerations in applications.

Overcurrent Earth Fault Protection (50P/51P; 50N/51N)

Overcurrent Earth Fault (OCEF) Protection is a **non-unit protection** provided as backup with time **discrimination** about 0.25s (for digital relays) – 0.4s (for EM relays) for **CT errors**, **relay overshoot** and **CB interrupting time**. OCEF setting for 11kV network is shown in Figure 1. The relay observes the current through CT primary and calculates tripping time with an **inverse** or **definite time** (e.g. SEF or HSOC) characteristics. Three phase currents flow through OC elements, tripping in **two out of three** (e.g. for KCGG142 OC2 elements) or separate logics for phase-to-phase fault, and the residual current goes into EF elements as in Figure 2. This allows separate time coordination between OC and EF elements. Another discrimination philosophy is based on a **blocking timer**, and the upstream is deblocked with **breaker failure protection** (BFP) as discussed below.

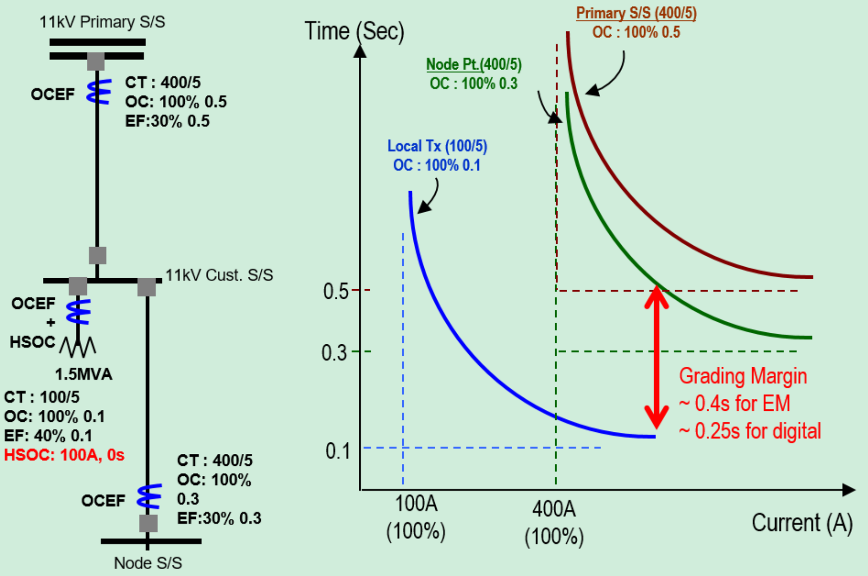


Figure 1: OCEF Setting in 11kV Network
& Time Discrimination between I-t Characteristics

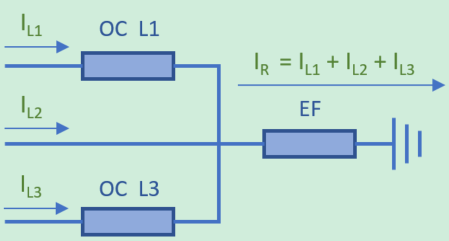


Figure 2: OC and EF Elements in OCEF relay

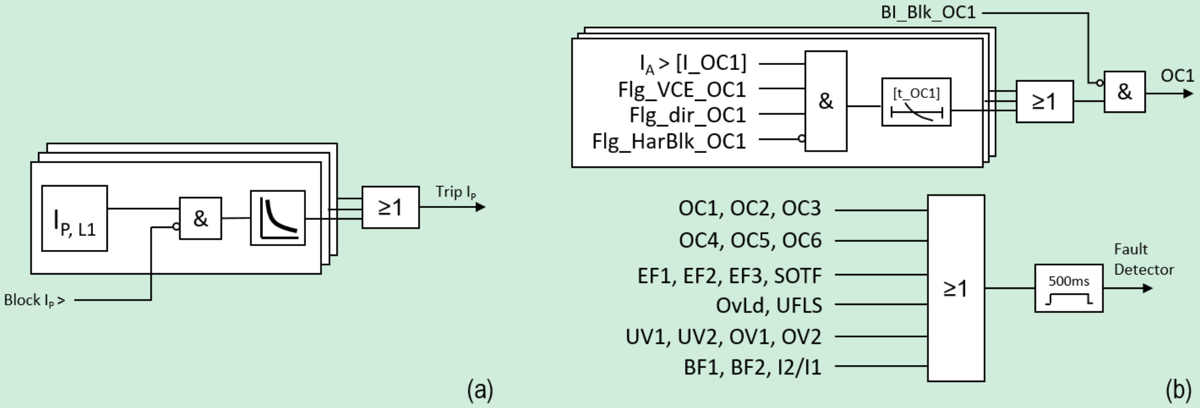


Figure 3: Logic Diagram of OC1 Element in (a) Siemen 7SJ602 & (b) NR RCS961

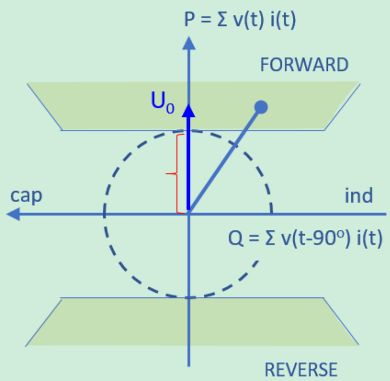


Figure 4: Directional Element Logic

Principles

OCEF relays, such as Siemen 7SJ610, NR RCS961 and KCGG142 implemented in our network, include 3 to 6 stages of **phase segregated** OC and 2 to 3 stages of EF, each with a **definite** or **inverse** characteristic. Phase segregation indicates faulty phase and provide faster response.

OC elements in 7SJ602 simply calculates the tripping time of respective current and trip if there is no blocking signal. It is **reset** (to avoid **flashing fault** or incipient fault) and prepared for next tripping after a defined time. 7SJ602 EF elements provides 2 stages of **sensitive earth fault** (SEF), one in inverse time and one in definite time, tripped with predefined delay. The EF elements include **neutral voltage displacement** (NVD) detection (observing $3U_0 = U_A + U_B + U_C > 0.02 - 0.05\ U_N$ with an **open delta**), and **direction discrimination** based on real and reactive power (P-Q) measurement as in Figure 4.

For RCS961, the OC element itself includes **voltage check** (U_{AB}, $U_{AC} < U_{P,SET}$ and $U_2 < U_{2,\ SET}$) due to <u>voltage collapse</u> in real fault, **direction check** (angle between I_A and any polarized voltage) for <u>fault location</u> in meshed or ring network and **harmonic block** (I_{2F}/I_{1F} > [K_2ndHarm], $I_A > 0.06 I_n$) due to inrush. Note: Another element with sensitive performance to inrush is I_A / I_0.

Digital relay allows additional features implementations with no significant costs.

- **Broken Conductor Detection** (BCD):
  It is implemented as an alarm to detect **unbalance** and **open pole**, especially in overhead

lines where loosened connection of jumpers often happens. The logic is based on a **statistical method** (max(I_A, I_B, I_C) – 4 min (I_A, I_B, I_C) > k_0, e.g. ABB Bay Relay for IPACS), **sequence network** (I_2 / I_1 > k_0, with I_1 > 0.04I_n, I_2 > 0.01I_n and CT supervision, e.g. RCS961 in Figure 5) and **undercurrent** (one of three phases is undercurrent, e.g. KCGG142). 7SJ602 has a 2-stage **unbalance** protection with OC check to trip with **negative sequence current** I_2.

– **Breaker Failure Protection** (BFP):
It is similar to BFP implemented in IPACS Bay Module as shown in Figure 6. If <u>current differential (CD) or OCEF</u> is triggered, in case there is still <u>current</u> (OC Check) after a <u>predesigned time</u> (300ms), BFP requests a **back-tripping** to upstream circuit breaker (CB) from high impedance busbar protection (HZBBZ) and the upstream CB isolates the fault. RCS961 requires also a <u>breaker status check</u> over the three requirements, and it allows a **re-tripping** of local CB to avoid BFP started by accident during maintenance.

– **Thermal Overload (OL, 49) and Cold Load Protection (CLP)**
To provide protection and detection to equipment under high load, alarm and tripping (110% I_{TH}), if necessary, can be set. This scheme employs temperature estimation with **current**, **thermal time constant** and **cable rating** (e.g. 90° for XLPE cable). 7SJ602 employs differential equation with thermal memory to provide estimation, while RCS961 utilizes an overload parameter I > [I_{OL}] to alarm or trip as in Figure 7. **Cold load protection** (CLP) is to

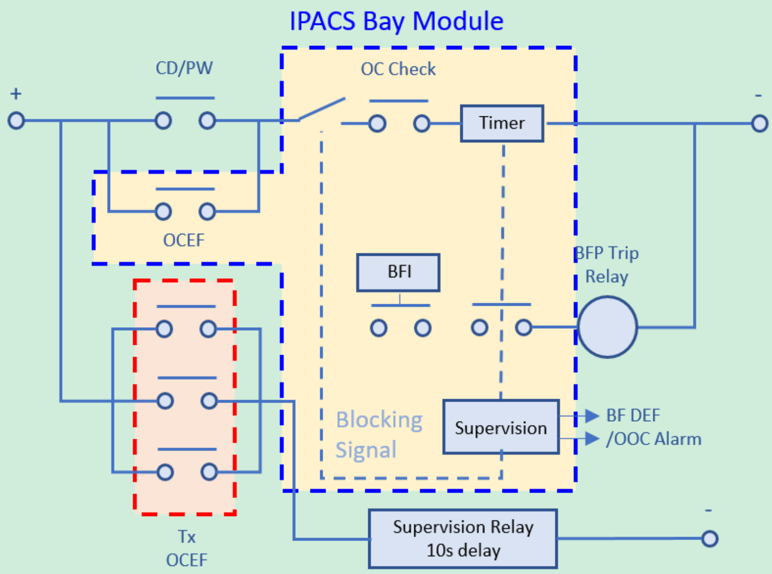
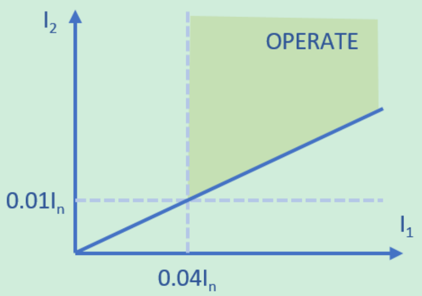


Figure 5: Operating Region for Open Pole and Unbalance

Figure 6: Breaker Failure Protection (ABB IPACS Bay Relay)



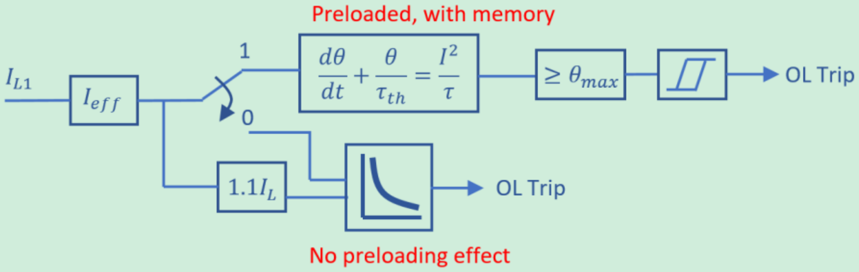


Figure 7: Thermal Overload Tripping (with and without Memory)

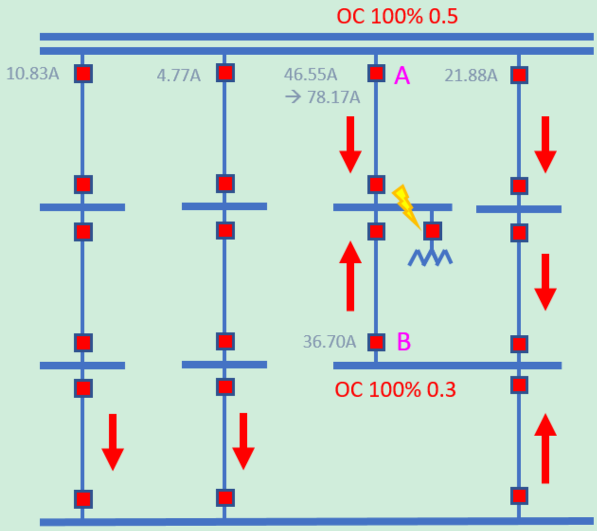


Figure 8: Typical 11kV Closed Ring with Current Distribution in the Legs

delay startup or modify OC setting during energization to avoid **load rejection** in network side. OCEF relay is often equipped with motor protection in which **motor startup time**, **restart inhibit** and **undercurrent** are applied. To provide time discrimination between closest CB, node CB and primary CB in 11kV closed-ring as in Figure 8, the OC setting employs inverse curves. Yet, the inverse curve has a nearly **flat region** with high current (> 20 times of pickup current) in which CB may not trip discriminatively if fault current is distributed evenly and large enough through the node point. Therefore, it is suggested to add a **directional check** in tripping logic as in Figure 9. Node CB should only be tripped if OC requirement is fulfilled and current flow should be out of node (forward). However, to provide directional check, a VT should be installed at node point for direction comparison. Yet, VT signal may not be reliable with **blown fuse** or under **close-in fault**, **VT Supervision** (VTS) should be provided and action is obsoleted if VT signal is loss.

Current Differential (87) / Pilot Wire Protection

Pilot Wire (Solkor Rf) Principles

Pilot wire protection, a unit protection, compares input and output current with a **summation CT** (L1:L2:L3 = 1:1:3) to

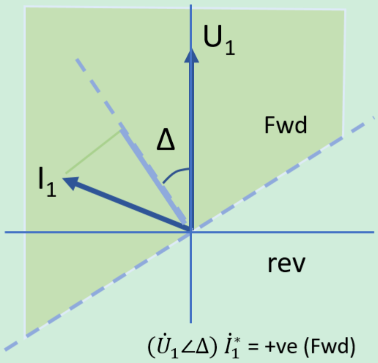


Figure 9: Directional Check with V-I Graph (Positive Sequence)

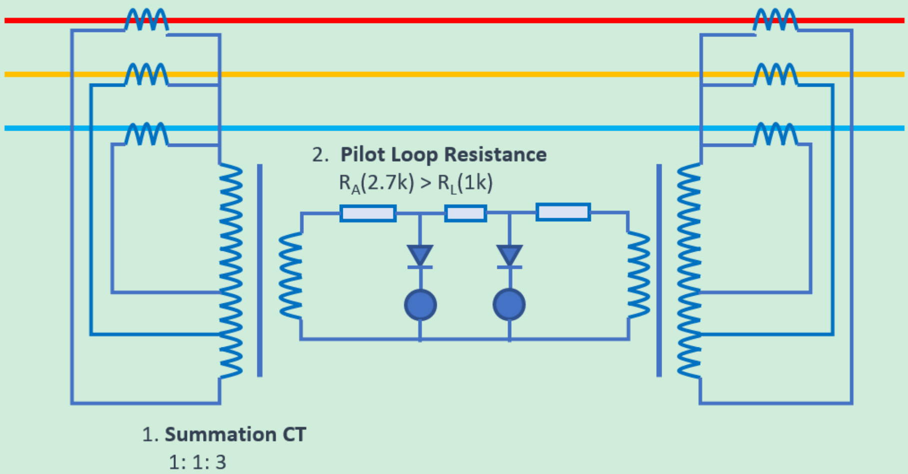


Figure 10: Solkor Relay Concept

take into consideration balance faults as shown in Figure 10. Current circulates in loop without going into the shunt branch for **external fault**. However, the actual operation of Solkor requires to **forward bias** the diode connected in series with the relay under positive voltage. Hence, the **pilot loop resistance** should not be larger than 1000 ohm to avoid introducing a positive voltage to the shunt branch even if it is an external fault. DC current flows through the pilot wire with power cable running in parallel in the same trench. Depending on the power cable voltage, pilot wire length, earth resistivity and screening, a large **induced voltage** (~ 5kV for 11kV network) is in the pilot wire. An **MOV** clamps the voltage before current entering the relay. In case the induced voltage is large than 5kV, an **isolation transformer** is needed to avoid posing harm to the relay and operation personnel.

To ensure no Solkor mis-operation, pilot integrity is checked with **Pilot Stability Test** (DSOM 0601). The test can be performed under on load and off load with primary or secondary injection. It is to test its core-to-core and core-to-earth **insulation**, **loop resistance** and **current** through relay and pilot under **normal**, **open** and **crossed** situation. The most common fault in pilot is **pilot low insulation** at joint. It is possible that Solkor is tripped with loosened pilot or CT connection, an **open pilot** case. During emergency or under on load testing, **Possible Unstable Protection** (PUSP) is raised with emergency OCEF and both pilot ends are shorted. For RMU Tee-point fault, to isolate the fault with remote CBs, **Pilot Unstabilizing** is utilized to open CB with open pilot.

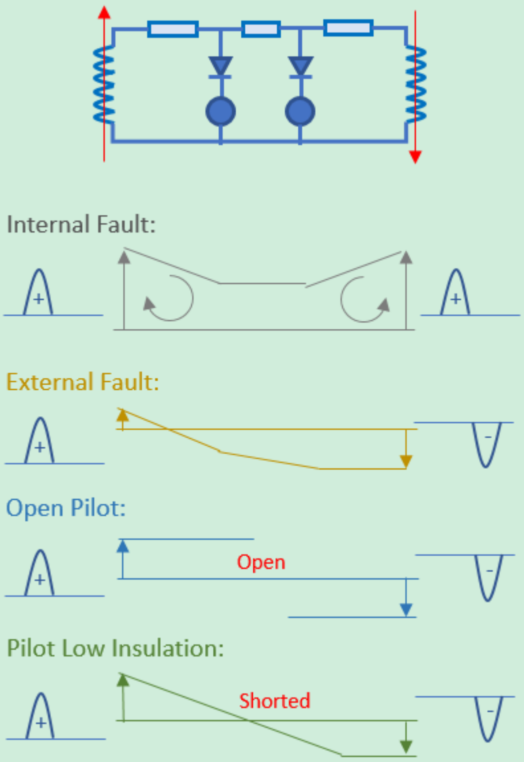


Figure 11: Voltage Profile of Different Scenario for Solkor

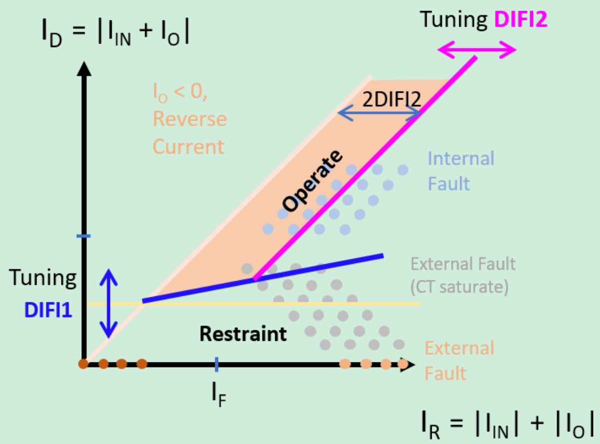
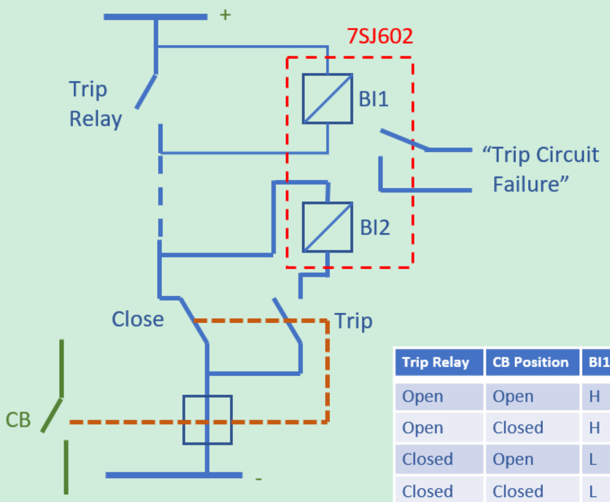


Figure 12: Current Differential (I_D – I_R Plane)



Trip Relay	CB Position	BI1	BI2
Open	Open	H	L
Open	Closed	H	H
Closed	Open	L	H
Closed	Closed	L	L

Figure 13: Trip Circuit Supervision in Siemens 7SJ602

A **phase segregated Current Differential** (CD) measures the input and output currents, determines their phasors (magnitude and phase angle) with **cosine filter**, and makes decision in tripping with an $I_D - I_R$ plane. I_D (or I_{OP}) is the operating current (or differential current) which vectorially sums up the currents, and the restraint current I_R is scalar sum of the currents. In case the $I_D - I_R$ point reaches the operating region due to internal fault, the CB tripping circuit is energized within 30ms. There are two settings DIFI1 and DIFI2 in the plane as shown in Figure 12. DIFI1 is the differential current with **minimum internal fault**. Slope 1 is to cater for increasing CT error with increasing current flowing through, while DIFI2 is larger than the full load current I_{FL} to differentiate **internal fault** and **external fault** even under severe CT saturation. DIFI2 should not trip also until overload in normal situation. Other than the described functionalities in OCEF, the implemented Toshiba GRL150, which employs this operating principle, integrates overcurrent check and fail safe operation with **current change detection** ($|I_{(t)} - I_{(t-1)}| > \Delta I_{SET}$). CD depends heavily on the **communication channel**, direct fiber and PCM multiplex. For monitoring, AC imbalance, memory check, watchdog, DC supply supervision, trip circuit supervision (Figure 13) and communication failure are provided. Some relays also provide **phase supervision** with negative (I_2) and zero (I_0) sequence current and derivative of positive sequence current (dI_1/dt).

In transmission overhead line, there is a large **charging current**, which is seen as a false differential, due to its parasitic capacitance as in Figure 14. This charging current often triggers current differential relay as the point reaches operating region in $I_D - I_R$ as in Figure 15. To solve this problem, **de-sensitization** with 1.5 cycles delay or implementation of **negative sequence current check** (I_2 > [I2set]) in I_{D2} - I_{R2} plane help. I_2 check also sensitizes unbalance fault detection. Yet, CD relay often comprises **load current compensation** ($I - I_{Pre\text{-}fault}$) and **charging current compensation**. **Self-compensation** for charging current is employed when voltage information is not available or not reliable. The current profile goes through a bandstop filter or is averaged to obtain compensation current or increase CD (87L) setting during line energization. **Voltage compensation** which calculates charging current ($I_C = C\, dv_s/dt$) with measured voltage in both remote and local. It is better to exclude **shunt reactor** from CD protection zone as line capacitance and shunt reactor compensates each other's effect and setting requires considerations with and without shunt reactor.

Other than charging current, **CT saturation**, **channel asymmetry** (i.e. delay over 90°) and **tapped load** are often sources of false differential. Although channel latency is the main concern, CD relays are immune to **evolving**, **inter-circuit** and **long-distance fault** or network phenomena such as **mutual induction**, **power swing** and **series impedance unbalance** as voltage information is not required as compared to directional.

Other than $I_D - I_R$ plane, which simply describes the vector sum and scalar sum and is favored for busbar protection with multiple input and output, **Alpha Plane**, a polar coordinated plane (I_R / I_L) for better magnitude and phase comparison, is often used in current differential as shown in Figure 16. It is more capable of presenting effect of **charging current**, **load current**, **communication delay**, **fault resistance** (R_F) and **CT saturation**. For alpha plane, the setting is just the angle and radius of the stable area. It is possible to employ phase (I_A), sequence (I_1, I_2, I_0) and residual (I_{RES}) current to operate this element. Charging current tries to pull out the current point out of the stable region; Load current provides a stabilizing effect to external fault, but not internal fault; Both communication delay and power angle and system impedance lead to an angular mismatch from the ideal point.

With an increasing fault resistance, the setting is insensitive to internal fault as in Figure 17, especially for the local internal fault, hence, a smaller stable region (smaller K in $I_D - I_R$ plane) is preferred. Yet, CT saturation with smaller K can mis-operate the relay. An open pole situation is also a reason to make the relay more unstable. It is suggested to block operation with a **broken conductor** and **CT status** check logic. Inrush can be detected by I_A/I_0 elements and filtered with I_2, which is less sensitive to harmonics. To further reduce the effect of loading and fault resistance, it is preferred to calculate the ratio with both elements with an **offset of pre-fault loading** as mentioned. Yet, this offset is more preferred to be implemented in I_2 and I_0 alpha plane, as both elements are sensitive enough to clear unbalanced and earth fault, while phase alpha element can keep its sensitivity with pre-fault information. Due to the cosine filter, CT saturation makes the saturated phasor shorter and leading. Only implementing I_0 is not preferred as I_A under saturation will have a flipping effect.

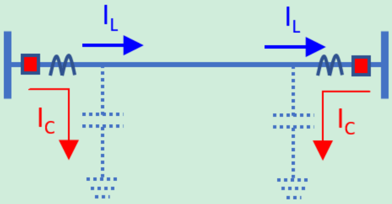


Figure 14: Charging Current and Loading Current Direction in Overhead Line

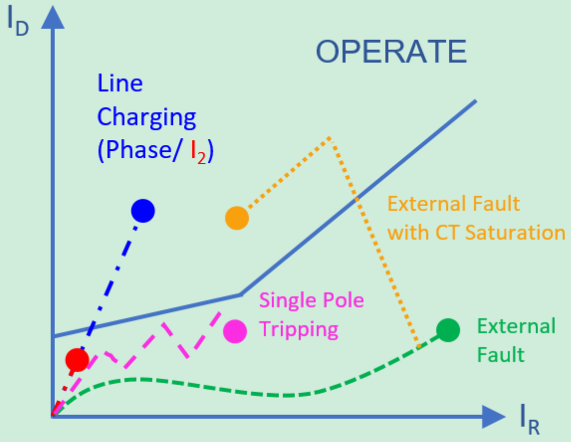


Figure 15: I_D – I_R Plane under Different Operating Conditions

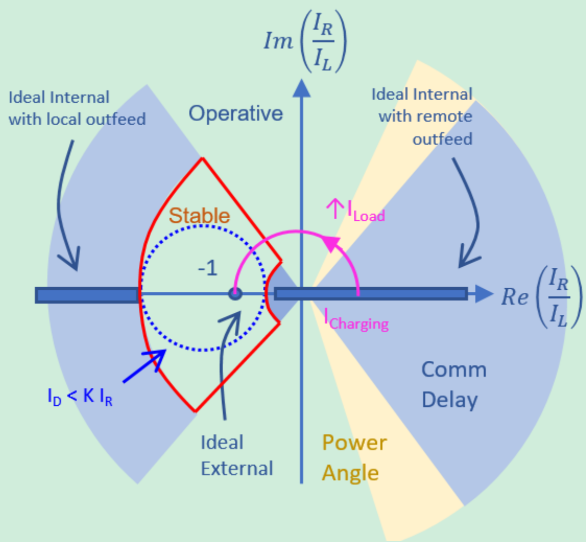


Figure 16: Alpha Plane Setting Considerations

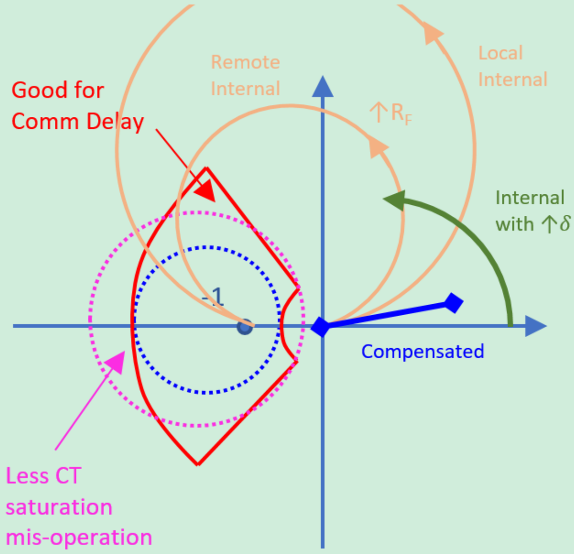


Figure 17: Alpha Plane under Different Operating Conditions

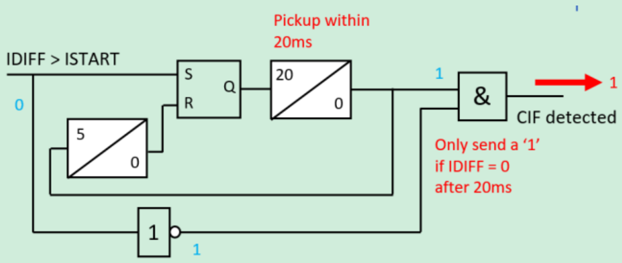


Figure 18: Cable Incipient Fault (CIF) Pickup Logic

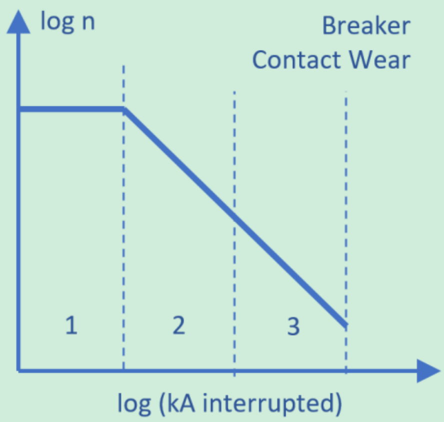


Figure 19: Breaker Contact Wear Alarm

Some bay relays (e.g. GE- P54A) allows customized logic setting for **conditional monitoring**. As a trial, logic for **cable incipient fault** (CIF) as illustrated in Figure 18 is being implemented. This logic detects any current surge larger than the pickup with duration shorter than 20ms, which is not considered as real fault. These surges are due to **partial discharge** and is considered as **flashing fault** if the insulation layer melts, then cools down and recovers its dielectric strength. If current returns to loading level within 20ms, the CIF counter latches and sends an alarm when three CIFs are picked up. As current differential is a unit-protection relay, it helps monitor cable health of each feeder with **fault location** capability, i.e. to identify if it is external or internal CIFs in each feeder.

Another condition monitoring philosophy comes to the circuit breakers. As **breaker contact wears** relates to **current interrupting capability** and **operation counts**, an alarm is given when the kA-interrupted parameter is smaller than the setting as in Figure 19.

Distance Protection

As discussed in previous monthly reports, distance protection, implemented with Omega 406, comprises **three zone settings**, **VT supervision** (VTS), **power swing blocking**, **SOTF**, **POTT/PUTT** and **echo scheme**.

In fact, distance protection determines its tripping with three approaches.

1. Calculates the **torque** $T = \mathrm{Re}\,(S_{OP}\, S_{POL}^*) > T_{SET}$
2. Calculates the measured **impedance** $Z_{Loop} = V_{Loop} / I_{Loop} < Z_{SET}$
3. Calculates the **projected distance** $m = \mathrm{Re}(V_{Loop}\, U_{POL}^*)/\mathrm{Re}(I\, Z_{Loop}\, U_{Pol}^*) < m_{SET}$

From the equations, a **voltage polarization** is required in distance relay. If phase A is faulty, the polarization could be U_A (**self-polarization**), -j U_{BC} (**cross polarization**), -j $U_{BC,Mem}$ (**cross polarization with memory**) and -j U_{Mem}^+ (**positive sequence memory polarization**). The last one is popular, as it is effective to detect **zero voltage close-in fault**, three phase fault and unbalance load before. It has improved **resistive coverage**, memory action for all faults and common references to the three phases. Another offset is to add a portion of line impedance (m IZ_{line}) to the measured voltage to cover close-in fault, but it may overreach the fault closed to remote CB.

In distance element, one popular discussion is **load encroachment**. Increasing load will have an underreaching effect to distance element with larger current and smaller load voltage. To ease setting, instead of a **quadrilateral** (with resistive, reactance, directional and negative resistance comparators) or a **blinder**, a load **blocking zone** is much preferred as shown in Figure 20. It preserves **loading capability** and **fault sensitivity**.

In transmission network, if a fault is not cleared within the **critical clearance time**, the generator starts to accelerate with power mismatch and losses its **synchronism** with the grid. Hence, faults in 400kV and 132kV must be cleared within 5 cycles (100ms) and 7 cycles (140ms) respectively. It is a **power system stability** concern. Yet, CB opening time requires at least 1.5 cycle (30ms) and cosine filter demands 1.25 cycles (25ms) to sample a full cycle and determines the phasor. **Channel latency** (5ms) is also a concern. It necessitates faster detections and operations. **Switch onto Fault** (SOTF), **Overreaching distance** (POTT) and **Differential element** (87L) have current input much larger than the setting. These do not require high accuracy in magnitude and phase to trip. For time domain operation, **high frequency incremental** and **travelling wave** approach provide must faster operation, possibly shorter than 1ms.

High Frequency Incremental (as describe in Figure 21) employs **notch filtering** ($\Delta s_{(t)} = s_{(t)} - s_{(t-p)}$) and **replica current** ($\Delta i_z = \frac{R_S}{|Z_S|}\Delta i + \frac{L_S}{|Z_S|}\frac{d}{dt}\Delta i$) to determine if the fault is overreached. The relative polarity indicates the fault direction, and the magnitude depends on both the system impedance and fault direction. The incremental signal Δv_F exhibits a step change when the voltage at the fault point collapses quickly and the fault is in zone. **Travelling Wave approach** can be used with **differential** and **distance** element (as describe in Figure 22). For distance element, it measures the time difference between two travelling wave and calculates the distance with speed. For differential element, it sets the operating and restraint currents as discussed before with real time data, given that it is assumed as an internal fault and operating current I_{OP} is large enough.

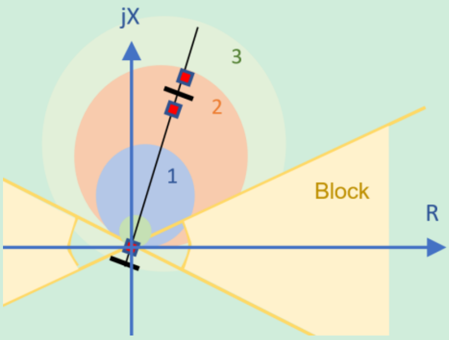


Figure 19: Distance Relay – Three Zone Setting and Load Blocking Zone

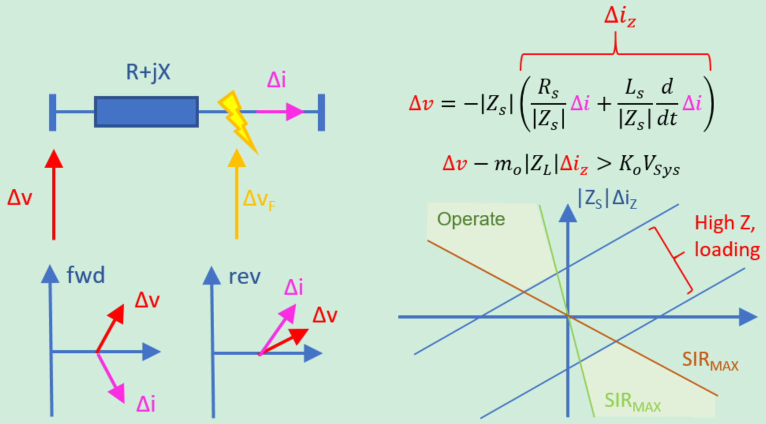


Figure 20: High Frequency Incremental Overreaching Element

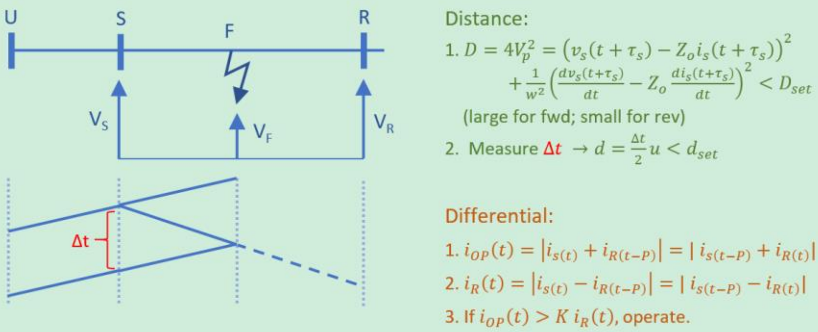


Figure 21: Travelling Waves Approach Distance Element & Differential Element

Conclusion

Feeder protection is important as it requires **sensitivity, speed, selectivity and stability** to clear feeder fault, which is most frequent and unavoidable fault in real life. This report discusses the main three operating principle (**directional** (overcurrent), **differential** and **distance**), their major setting consideration with **network behavior** and their additional functions available for better protection, control and monitoring. It is easy to understand the operating principle, but it is hard to identify all possible network scenario which may violate the setting as protection specialist expected. More and more uncertainties, including **renewable energy**, **electric vehicles charging stations**, **HVDCs** and **demand responses**, occurs in grid and it requires a protection specialist to understand all network behavior and interaction to support grid planning and operation.