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Loss-of-Potential Detection for Generator Relays

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A B S T R A C T

Fuses often protect the generator potential transformer (PT) secondary wiring. The operation of one or more fuses results in loss-of-potential (LOP) inputs to the relay. Furthermore, a partial or complete LOP condition can occur due to the failure of an aging PT, secondary wiring, or relay input failures. The fast and reliable detection of LOP conditions are essential for the security of voltage-based protection functions in generator relays. Traditionally, in electromechanical protection schemes, an LOP condition was detected by a comparison of the three-phase voltages from two PTs or a PT with dual-secondary windings using a so-called voltage balance relay. With the advent of modern digital relays came current-supervised LOP detection schemes. In this paper, we provide insight into the unique aspects of generator LOP detection. We examine different methods of detecting LOP and compare their advantages and shortcomings. Finally, we present several novel enhancements to generator LOP detection schemes.

1. Introduction

Several generator protection functions rely on stepped-down voltage measurements from the generator terminal. A variety of events, collectively known as loss of potential (LOP), can impact the health of these measurements. These include the following:

- A secondary wiring short circuit can occur due to insulation damage or human error. This can lead to the operation of a secondary fuse or miniature circuit breakers (MCBs).
- A secondary wiring open circuit can occur due to a loose connection in a terminal block or a poor wire crimp.
- A shorted turn or turns within the potential transformer (PT) can evolve into an internal fault and lead to the operation of the primary fuse.
- A problem with the isolating (racking) mechanism can cause an open circuit.
- The secondary fuses can be removed or an MCB opened during maintenance and not subsequently restored prior to placing the generator back in service.
- The analog circuitry of the relay can fail.

An LOP event can involve one, two, or three phases. It can cause partial or complete LOP. It can be permanent or intermittent.

2. PT Connections and Fuses

Unlike current transformers (CTs), which are magnetically coupled, PTs need to be tapped to the leads to obtain voltage measurements. References[1] and[2] provide classification regarding the winding connections. Fuses provide protection to the secondary circuit in most cases, except for connections like wye-grounded, closed-delta connections in which a high zero- sequence current may circulate in the delta winding, causing damage to the PT. It is advisable to avoid this possibility. Fuses also provide isolation from the secondary faults, inducing current in the primary. Different PT connection diagrams with fuse locations are shown in the following figures. See Fig. 1, Fig. 2, Fig. 3, and Fig. 4. A, B, and C are generator leads.

2.1. Phase-to-Phase Primary and Phase-to-Phase Secondary

In Fig. 1, the primary winding connection is phase to phase, and the secondary winding connection is also phase to phase, given by ab and cb for phase-to-phase burden. Zero sequence is lost in this connection, and ca can be derived from ab and cb.

2.2. Phase-to-Ground Primary and Phase-to-Ground Secondary

The primary winding connection in Fig. 2 is phase to ground, and the secondary winding connection is phase to ground, given by a, b, and c for the phase-to-neutral burden.

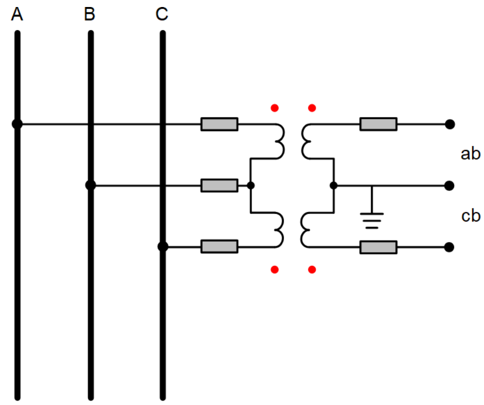

Fig. 1. Phase-to-phase primary and phase-to-phase secondary PT connections.

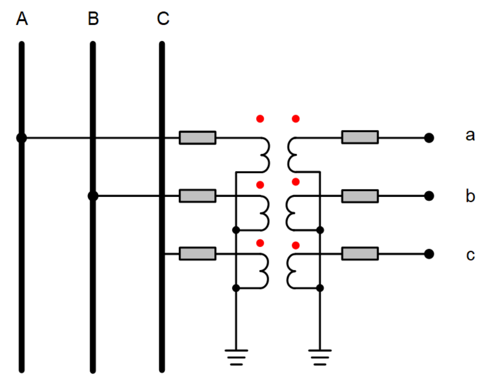

Fig. 2. Phase-to-ground primary and phase-to-ground secondary PT connections.

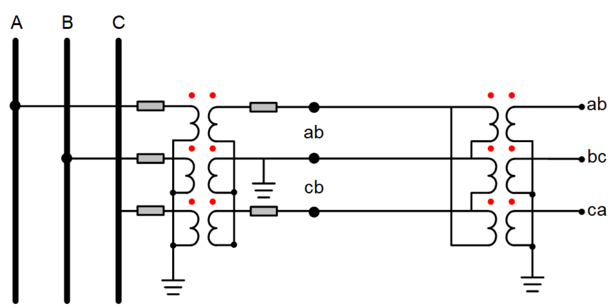

Fig. 3. Phase-to-ground primary and phase-to-phase secondary with auxiliary PT connections.

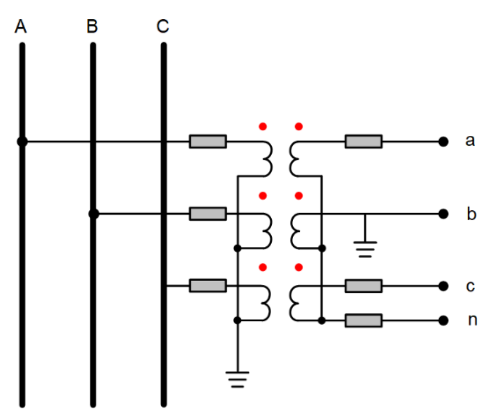

Fig. 4. Phase-to-ground primary and phase-to-ground secondary with shifted-ground PT connections.

2.3. *Phase-to-Ground Primary and Phase-to-Phase Secondary*

The primary winding connection in Fig. 3 is phase to ground, and the secondary winding connection is phase to phase, given by ab and cb for phase-to-phase burden or ab, bc, and ca for phase-to-neutral burden obtained from an auxiliary PT. This connection is used mainly to compensate for the phase-angle shift of the generator step-up transformer in electromechanical relays. Zero sequence is lost in this connection.

2.4. *Phase-to-Ground Primary and Phase-to-Neutral Secondary With Shifted Neutral*

The primary winding connection in Fig. 4 is phase to ground, and the secondary winding connection is also phase to ground; but similar to Fig. 3, the ground is placed on the b-phase, and the neutral is shifted by –b. The neutral is to be connected to the relay neutral, and zero sequence is preserved in this connection.

Proper care must be exercised to make sure that the PT connections do not interfere with the ground fault protection of the system. Connections A and C do not interfere with the ground fault protection in the case of faults in PT secondary involving the ground, avoiding the need for coordination between fuses and the generator stator ground protection. For Connection B, zero-sequence voltage may appear at the generator neutral for a PT secondary fault interfering with the stator ground fault protection, so the fuses need to be coordinated with the system ground protection. For Connection D, only secondary ground faults in the neutral lead will interfere with the generator ground fault protection. This is essential in the case of a high-resistance-grounded generators commonly found in unit-connected generating units. Also, PTs in the case of winding faults need to be isolated from the systems, which can be done with a primary fuse. So, it has become common practice to include fuses in both the PT primary and secondary.

3. Impact of LOP on Generator Protection Reliability

The reliability of a protection system is subdivided into dependability and security. A dependable protection system operates for faults within its zone. A secure protection system does not operate for anything that is not an internal fault.

To assess the impact of LOP on reliability, we turn to the work of Sandoval[3]. This reference is more than a decade old. Some of the reliability metrics may, therefore, be out of date; however, the underlying analysis is sound, and the results are useful to contrast an LOP condition with other failures.

Dependability can be equated to availability (A) and defined as the amount of time a system is available to operate divided by the total operating time. Unavailability (U) is equal to $1 - A$ and is approximated as the mean time to repair (MTTR) and mean time between failures (MTBF). The MTTR includes the time to detect the failure and the time to carry out a repair or replacement of the failed device. An MTBF of 360 years is used for a single PT failure. Assuming immediate detection and a replacement time of 2 days yields an unavailability of $3 \times 15 \times 10^{-6}$. We focus on a dual-redundant scheme using Relays A and B with duplicate CTs, PTs, and control wiring. This is arguably the most common redundancy scheme for large generator protection. The dependability fault tree is shown in Fig. 5. Reference[3] details the construction of the fault tree, the sources for the individual unavailability values, and the methodology used for calculating the overall unavailability.

Individual unavailabilities are shown for each type of failure. It is notable that PT unavailability is relatively low as compared with

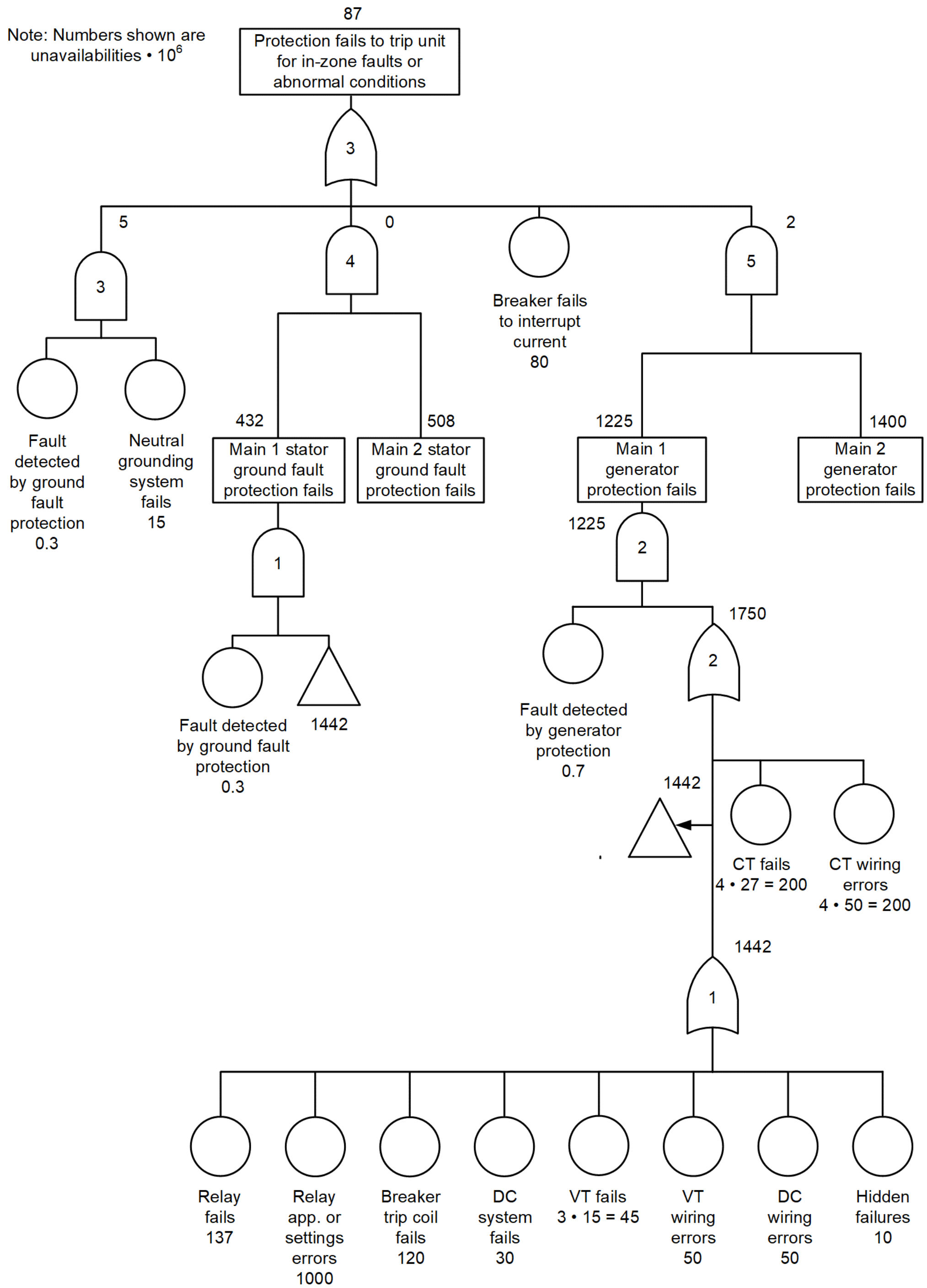

Fig. 5. Dependability fault tree for the dual-redundant generator protection scheme using relays from the same manufacturer[3].

other failures and significantly smaller than a relay setting error (1000). When combined with the other failures, the total unavailability (shown at the top of Fig. 5) can be determined in (1).as

$$U_{\text{MAIN 1}} := 0.7 \times (1\,750 - 45 + 45) = 1.225 \times 10^3$$
$$U_{\text{MAIN 1}} := 0.7 \times (2\,000 - 45 + 45) = 1.4 \times 10^3$$
$$U_{\text{total}} := 0.3 \times 15 + 80 + \frac{432 \times 508}{10^6} + \frac{U_{\text{MAIN 1}} U_{\text{MAIN 2}}}{10^6} = 86.434 \quad (1)$$

A significant reduction in total unavailability is realized by the use of a dual-redundancy scheme.

LOP detection does not affect MTBF but does have a significant impact on MTTR. With effective LOP detection the MTTR is equal to the replacement time of the failed device, which is estimated at 2 days. Without LOP detection, we may assume that an LOP condition will only be detected during scheduled maintenance, giving an estimated MTTR of 2 years.

Without LOP detection, unavailability for a PT failure increases to $2/360 = 5\,556 \times 10^{-6}$. Unavailability due to a PT failure is now dominant. The resulting total unavailability is

$$U_{\text{MAIN 1}} := 0.7 \times (1\,750 - 45 + 5\,556) = 5.083 \times 10^3$$
$$U_{\text{MAIN 1}} := 0.7 \times (2\,000 - 45 + 5\,556) = 5.258 \times 10^3$$
$$U_{\text{total}} := 0.3 \times 15 + 80 + \frac{432 \times 508}{10^6} + \frac{U_{\text{MAIN 1}} U_{\text{MAIN 2}}}{10^6} = 111.443 \quad (2)$$

This represents an increase of $(111.4 - 86.4)/86.4 = 28.9\%$. A similar exercise can be carried out to assess the impact of LOP detection unavailability on security.

4. Considerations for Generator Protection

Energizing a synchronous machine often follows a particular order: getting the rotor to near synchronous speed, closing the field breaker, and then closing the main/synchronizing breaker. However, there are some applications in which the field is energized from a standstill, e.g., large cross-compound steam units, some pumped storage hydro units, and gas turbines with a static frequency converter. Ideally, the generator protective relays should be operational and able to detect faults for the duration of starting. The relay elements, like 87, 24, and 64G, should be able to detect a fault and provide a trip that will prevent further damage to the generator. Of these, voltage-dependent functions should be supervised with LOP to make a valid trip decision, even when operating with the synchronizing breaker open.

For example, it is evident in the case of generator relays that the undervoltage element loses security and the overvoltage element loses dependability during LOP conditions. We turn our attention to other protection functions that are affected by the LOP conditions mentioned in the following sections.

4.1. Inadvertent Energization

Inadvertent energization protection (INAD) is armed when the generator is offline to protect against an accidental closing of the breaker, which could result in high currents, and when the generator starts acting as a motor drawing power from the connected system. The arming logic is often an undervoltage element. If not properly supervised by LOP, the voltage input failure could arm the INAD element and trip the generator. The following simulated event capture (Fig. 6) shows the INAD element picking up during the generator loading during a two- phase LOP condition. VA/VB/VC and IA/IB/IC are generator terminal voltages and currents in secondary.

4.2. 32P Power Elements

Directional power elements need accurate voltage inputs to calculate active and reactive power to provide reliable protection against abnormal operating conditions. The operation of one or more fuses in the PTs could lower the real and reactive power, as seen by the relay. During such conditions, a reverse power element will likely lose dependability, and a low-forward power element could lose security.

4.3. Backup Protection

In addition to the protection for different faults in the generator zone, it is common practice to provide backup protection for external faults that are not cleared in a timely manner[4]. It has also been common practice to employ backup distance protection when the connected lines are protected with distance elements and employ overcurrent elements for lines with overcurrent element protection. Backup overcurrent elements must be supervised or restrained with voltage since the fault current will decrease to a value less than the load current prior to time-out.

4.3.1. 21P Phase Distance Element

Impedance determination in backup phase distance protection is affected by LOP conditions. Calculations made from reduced voltage, as a result of an LOP, appear as an in-zone fault to the relay, which in turn could result in an undesired trip operation.

4.3.2. 51C/51V Overcurrent Elements

The voltage supervision in the voltage-controlled overcurrent element (51C) allows a sensitive current pickup. During LOP conditions, the voltage supervision asserts and 51C operates for load current. Another variation of backup overcurrent protection is the voltage-restrained overcurrent element (51V), in which the current pickup varies in proportion to the voltage. The loss of voltage input lowers

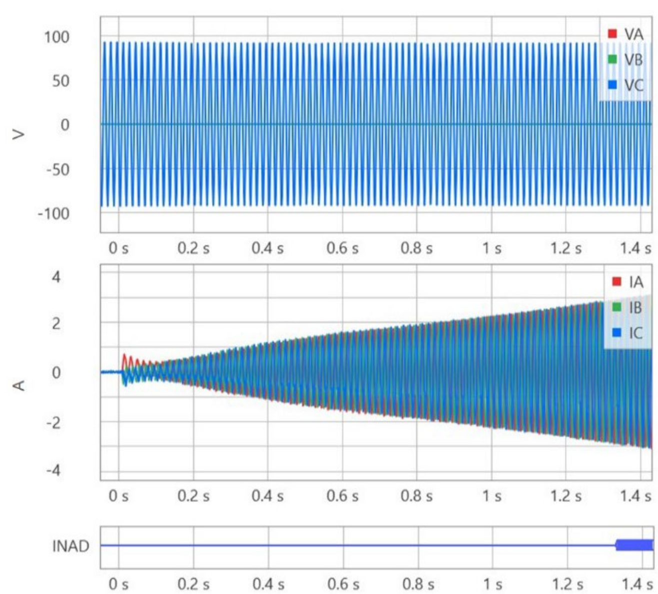

Fig. 6. Event report showing the INAD element picking up during generator loading.

the pickup and results in an undesired trip during normal operating conditions. All the backup elements, irrespective of the type of backup protection employed, require reliable, accurate voltage measurements. It is, therefore, essential to supervise the backup elements with LOP to maintain the security of the generator protection.

4.4. 24 V/Hz Element

The dependability of the V/Hz element is lost during LOP conditions. In electromechanical relays, the voltage and frequency are derived from a single line-to-line or line-to- ground voltage input. The V/Hz element is only affected when that particular phase voltage input failure occurs. Modern relays also calculate the frequency from the voltage waveform; and, therefore, the V/Hz element solely depends on reliable voltage inputs. During LOP conditions, a V/Hz element based on positive-sequence voltage sees voltage at around 67 percent and at 33 percent of actual levels for one- and two-phase fuse operations, respectively, for wye-connected PTs. The frequency derived with the healthy voltage inputs will be rated for a generator that is online. For a 20 percent increase in excitation in which the element is supposed to operate, the relay will see V/Hz less than the rated value not resulting in a trip. In comparison, a per-phase-based V/Hz element can detect overexcitation in partial LOP conditions from the healthy phase inputs, making the three-phase LOP the only condition that the 24 element cannot provide overexcitation protection.

4.5. 81 Frequency Elements

As previously established, the frequency for generator protection is determined by voltage inputs and can even be calculated from one healthy phase voltage measurement. Unlike other elements, which are affected by the failure of single-potential input, frequency elements are secure during the loss of one or two potential conditions. Frequency elements are only affected by full LOP conditions, i.e., all three phases. Therefore, frequency elements are often supervised with undervoltage elements with pickup around 20 percent of the nominal voltage. The frequency can be determined from the current waveform during a complete LOP condition.

4.6. Directional Element

Modern multifunction generator relays may offer feeder protection for unit auxiliaries that sometimes require directional supervision. Directional determination that uses voltage becomes unreliable during voltage input failure conditions, which could result in an undesired operation for out-of-zone faults.

4.7. 40Z Loss-of-Field (LOF) Element

The LOF element usually comprises two impedance zones. Zone 1 is set to trip faster (0.1 s) under severe conditions when compared to Zone 2, which may be set to operate slower (0.5 to 0.6 s), to ride through stable power swings that may encroach into Zone 2. During the loss of one or two potentials, a stable power swing could result in an apparent impedance entering Zone 1, issuing a trip before giving the system a chance to stabilize. Another situation when LOP might affect LOF protection is when operating the machine as a synchronous condenser, which often operates closer to the LOF impedance characteristic. It has been common practice to employ LOF protection in conjunction with a sensitively set (usually 90 to 95 percent) undervoltage element to provide security[4]. If not appropriately supervised by LOP logic, it may result in an undesired trip.

4.8. 78 Out-of-Step (OOS) Element

OOS protection is generally used to protect the system against unstable power swings that would result in loss of synchronism. There are many schemes that detect an out-of- synchronism event but have the same underlying operating principle, which detects the positive-sequence impedance trajectory from the normal load region (positive R region) to the opposite side (negative R region) in the RX plane for an unstable power swing. Some systems, like a double-blinder scheme, depend solely on measuring the time to cross the regions, indirectly calculating the speed of the swing to differentiate between the fault and power swing. Since the schemes use impedance, which relies on voltage measurements, it has been a common practice to supervise the OOS element with LOP logic.

The loss of all three potentials may not affect the security of the OOS protection. The loss of one or two potentials without a power swing does not result in a loss of security since the impedance locus does not traverse the path of a power swing. The security of the OOS element is lost in the event of an unstable power swing on the transmission system coincident with the loss of one or two potential inputs since the apparent impedance moves closer to the origin. In this case, supervising the OOS element with LOP would block it from operating.

4.9. 64G2 Element

Coverage for stator ground faults near the neutral of the generator is provided by the third-harmonic voltage-based differential protection scheme, 64G2 element[5]. This element relies on accurate voltage measurement, and any inaccuracies (such as a blown fuse) results in undesired tripping of the generator unit. In addition, Fig. 7 refers to a field event where one of the phase PT is compromised. VAX/VBX/VCX are generator terminal voltages, VP0 is the zero-sequence voltage derived by summing terminal voltages, and VN is the voltage at the generator neutral. The function responds to the difference between VP0 and VN, resulting in an undesired operation. Supervising the stator ground protection elements with LOP will avoid undesired tripping and improve the security.

5. LOP Detection Schemes

In the discussion so far, we have established the importance of LOP detection and how the dependability and security of generator protection is improved by LOP supervision. The following section describes various ways to detect LOP conditions along with pros and cons for each scheme.

5.1. Voltage Balance Scheme

The voltage balance scheme, which is predominantly used in electromechanical relay schemes, can be applied to systems that have two sets of PTs, as shown in Fig. 8(a) and Fig. 8(b) or a PT with dual secondaries, as shown in Fig. 8(c). In this scheme, the individual phase voltages from the PT are compared with phase voltages of the second PT. This scheme is phase- segregated. One advantage of a voltage balance LOP scheme is that it is sensitive and secure for all operating conditions, including when the generator is offline. The drawback of this scheme is that it needs six voltage measurements requiring a second PT or a PT with dual secondaries. For the configuration in Fig. 8(b), PTs are on either side of the synchronizing breaker; therefore, this scheme needs to be blocked when the generator is offline. This scheme is unavailable in the case of a primary fuse operation in Fig. 8(c).

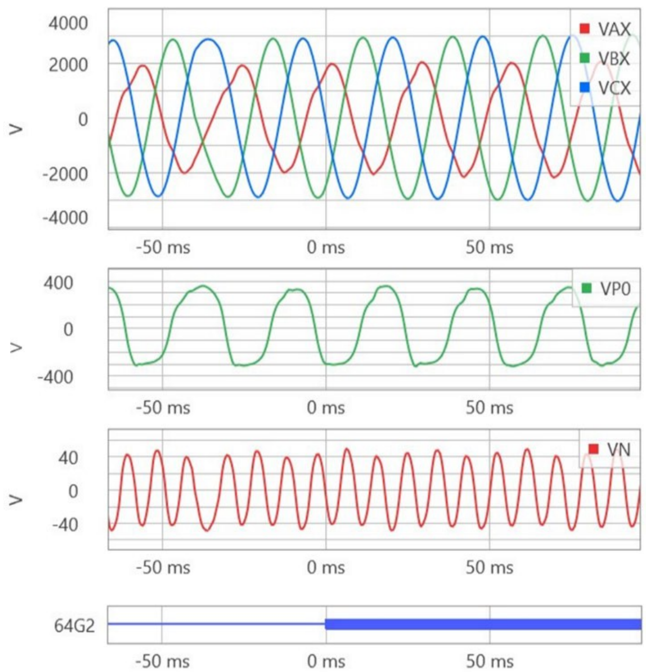

Fig. 7. Event report showing generator terminal and neutral voltages during a 64G2 misoperation.

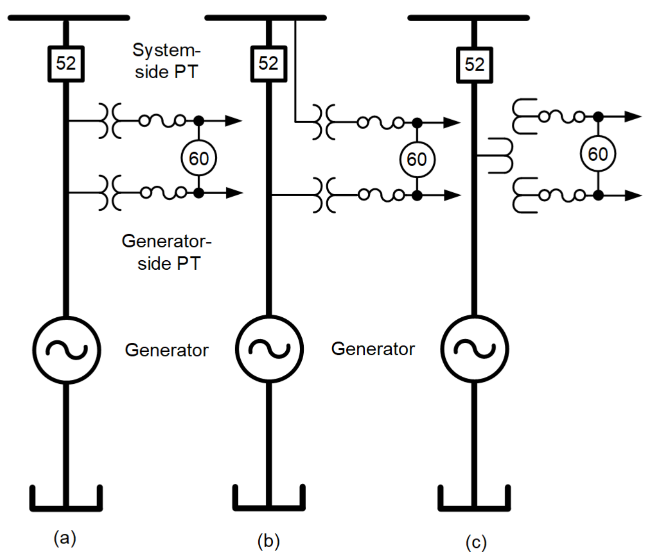

Fig. 8. Voltage balance LOP scheme.

The calculation of the sequence quantities becomes easy to implement with the advent of microprocessor relays. The per-phase-based voltage balance scheme can be simplified with the use of a positive-sequence voltage.

5.2. *Improvement: Positive-Sequence Voltage Balance Scheme*

Fig. 9 shows a voltage balance scheme based on a positive- sequence voltage that can be used to determine the LOP condition. This method determines LOP conditions by calculating differential positive-sequence voltage with inputs from both PTs and compares it with certain pickup thresholds. The sign of the differential voltage can give us the indication of the failed PT as well.

scheme.

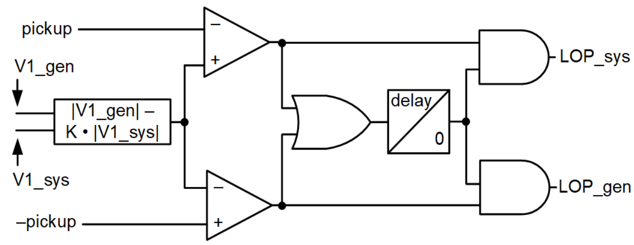

Fig. 9. Positive-sequence-based voltage balance LOP.

This scheme can be applied independently of the PT connections described in Section II, unlike the per-phase-based scheme that requires similar connections on both PTs. Furthermore, considering the limited number of relay voltage inputs, this scheme allows for detecting LOP with four voltages when PT secondaries are in phase-to-phase connections, allowing the additional available voltage inputs to be used for other purposes, like synchronization (the need for connection in Fig. 8(b) and neutral voltage measurements. The voltage inputs to protection functions can be switched to alternate healthy PTs using a failed PT indication. The advantages of the traditional voltage balance scheme, sensitivity, and security are still valid for this implementation.

5.3. *Voltage Current Schemes*

To reduce the number of relay voltage inputs and remove the need for a second PT, the following current-supervised schemes are developed. When a disturbance occurs in a power system, a change is observed in both the current and voltage values, and the relay senses the same. Alternatively, in the event of an LOP, there is no change in the current input to the relay, but the voltage as seen by the relay changes. The voltage current schemes are based on this feature.

5.3.1. *Incremental Change Scheme*

The incremental change scheme works on disturbance detections using incremental quantities. The term “incremental” is defined as change in a quantity over time. The incremental change scheme detects LOP conditions by monitoring a drop in the positive-sequence voltage without a change in currents. Fig. 10 shows the logic for the incremental LOP method. DV and DI are incremental voltage and current quantities. The timer delay1 is set to be able to detect current disturbance for slower events. The timer delay2 is set to block LOP for certain times during system disturbances to avoid nuisance alarms.

The incremental change scheme method can detect both symmetrical and unsymmetrical LOP conditions when the system is energized. This scheme may give a nuisance alarm in case of ground faults in high-resistance-grounded machines. This scheme does not assert in the case of an evolving PT failure in which the voltage change is gradual.

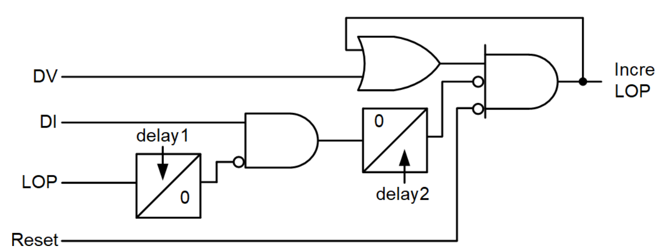

Fig. 10. Incremental-change-based voltage current LOP scheme.

This scheme detects LOP conditions, even when the synchronizing breaker is open with the generator energized, but it may spuriously latch on for voltage change by the automatic voltage regulator or during a normal generator shut-down. It is, therefore, advised to supervise this scheme with the status of the synchronizing breaker.

5.3.2. Voltage Current Unbalance Scheme

LOP conditions can also be identified with the presence of a negative-sequence voltage without the presence of a negative-sequence current. The use of zero sequence instead of negative sequence is not encouraged because a zero-sequence-based scheme cannot detect disturbances like phase faults, and it is also affected by ground faults in high-impedance grounded generator systems, when there is little to no change in current. Furthermore, zero-sequence voltage is unavailable in PTs connected in delta. Fig. 11 shows the LOP logic diagram for a negative-sequence-based voltage current scheme, also known as a voltage unbalance scheme.

In Fig. 11, $|V_1|$ and $|V_2|$ are positive- and negative-sequence voltage magnitudes, and $|I_1|$ and $|I_2|$ are positive- and negative- sequence current magnitudes, and I_{NOM} is the nominal current.

The negative-sequence-based LOP logic should be supervised with minimum positive-sequence voltage and current to check the validity of the measurements. The main advantage of using this scheme is that it can detect LOP conditions when the voltage is decaying slowly, which is a limitation in the incremental change scheme. This scheme cannot detect complete LOP involving all three phases, which can be done through using the incremental change scheme. This scheme cannot detect LOP when the synchronizing breaker is open.

Seeing as how both the unbalance scheme and the incremental change scheme complement each other in most of the cases, it is advised to use them together to cover the majority of the scenarios. To detect LOP condition when the generator is offline, we propose the following improvements.

5.4. Improvement: Offline Detection

LOP during breaker open conditions can be detected by sensing the presence of a negative-sequence voltage or the absence of a positive-sequence voltage with the generator field energized. Fig. 12 shows the logic diagram of the offline LOP scheme.

This scheme requires a positive indication that the generator is energized. Any of the following three methods may be considered to provide this indication.

The first method is using a field breaker position contact wired to the relay to sense the generator energization.

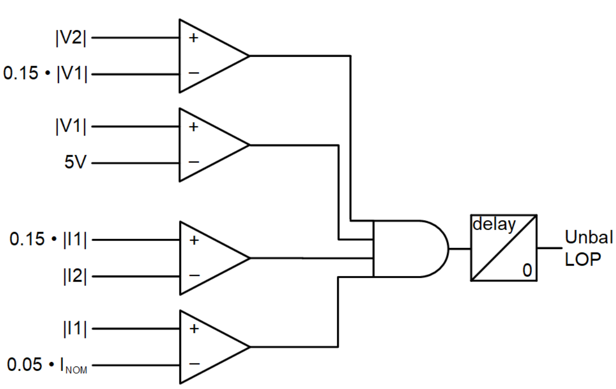

Fig. 11. Unbalance-based current-supervised LOP scheme.

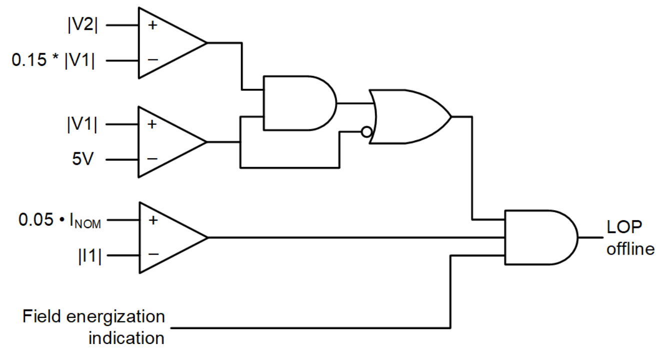

Fig. 12. Offline LOP scheme.

The second method is field current detection. Some generator relays may be equipped with transducer inputs and analog comparators that can be used for this purpose.

The last method is third-harmonic voltage detection. On virtually all high-resistance-grounded generators, the relay measures the generator neutral voltage for ground fault protection. Furthermore, most of these generators have a standing third-harmonic voltage drop at the neutral. Most generator protection relays are equipped with third-harmonic schemes for 100 percent stator ground protection. Some relays may also include analog comparators that can be used to indicate the presence of the third-harmonic voltage. The advantage of this method over the first two described previously is that the indication may already be present in the relay. However, the third-harmonic level needs to be checked to confirm that the signal is reliable. Many relays allow the third harmonic to be trended to facilitate this confirmation. Using the ORed input of all available methods gives the most reliable indication of field energization.

The scheme is disabled as soon as the generator is online since it is no longer needed. LOP while offline can also be detected with the following terminal voltage-estimation-based scheme.

5.5. Improvement: Field-Current-Based Voltage Balance Scheme

Traditionally, a voltage balance scheme needs two sets of three-phase voltages to detect an LOP condition, in which we compare one set of the voltage inputs against the secondary inputs. The need for second three-phase inputs can be replaced by an offline estimate[6] of the voltage magnitude at the terminal of the generator, as

$$V_{\text{est}} = \omega L_{ad} I_{\text{field}} \tag{3}$$

In (3), L_{ad} is the direct axis mutual inductance between stator and field winding of the generator, ω is the measured radian frequency. L_{ad} can be obtained from a machine open circuit characteristic. Note that (3) does not take residual flux into consideration. The resulting logic is shown in Fig. 13.

In this implementation, the scheme is supervised by a current-based offline check. This scheme will be unavailable if the field current

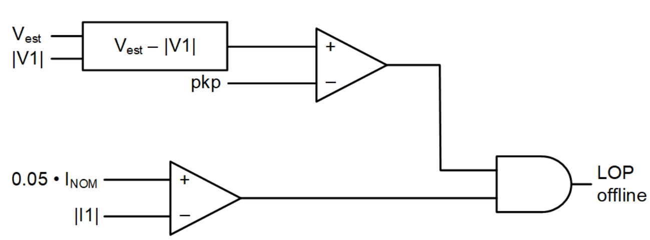

Fig. 13. Field-current-based voltage balance scheme.

measurement fails or if the speed measurement fails when used for deriving frequency. This scheme is potentially more sensitive than the offline LOP scheme in the previous section since it compares the measured voltage with the estimated value. This scheme needs either frequency or speed measurement for the entire range of offline operation.

6. Conclusion

Many generator protection functions rely on accurate voltage from the generator terminals. The failures in the PT circuit cause the relay to lose dependability and security, which can occur for any number of reasons. To improve reliability, relays need to be employed with adequate LOP detection mechanisms supervising the protection elements. Different types of connections available for generator PTs are mentioned. The security of various voltage-dependent generator protection functions, like INAD, 32P, 40, 78, 64G2, and generator backup protection, is lost during LOP conditions. The dependability of the 24 V/Hz and 81 elements may be affected during LOP conditions. In some cases, certain backup protection is required when the reliability of the primary protection is lost during LOP conditions.

The traditional voltage balance scheme is the most sensitive method to detect an LOP condition, but it requires two sets of voltage inputs. The current-supervised LOP detection schemes, which use negative-sequence voltages together with incremental change schemes, can be used to detect LOP conditions with inputs from one set of voltage inputs, but they are not secure during offline conditions. The proposed offline LOP detection scheme provides proper LOP indication using neutral third-harmonic voltage/field indication when the breaker is open. Alternatively, a novel terminal voltage- estimation-based offline scheme using field current can be used to sensitively determine LOP.

Acknowledgment

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