

Pumped Storage Hydro Protection – Application Considerations

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Pumped storage hydro protection – application considerations

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Abstract:

Currently the U.S. has about 20 GW of pumped storage hydro with an additional 30 GW of new capacity being proposed for support of renewable sources. Switching a reversible pumped storage hydro unit from generator to pumping mode can impact the differential element and elements that use sequence components. Furthermore, protecting units that start as induction motors requires protection of the damper winding during the starting and acceleration period. Stopping or braking the unit before reversing its rotation also requires special protection considerations. This paper discusses the advantages that digital protective relays have over traditional protective relays when protecting pumped storage hydro units.

1 Introduction

During the last two decades, renewable energy projects have gained momentum, and at present a large installed base of wind and solar energy sources exists worldwide. These sources are intermittent, and maintaining grid stability requires bulk energy storage.

Pumped storage hydro (PSH) units are hydro units that can operate in generating or pumping mode, moving water either from the upper reservoir to the lower reservoir or vice versa, as shown in Fig. 1.

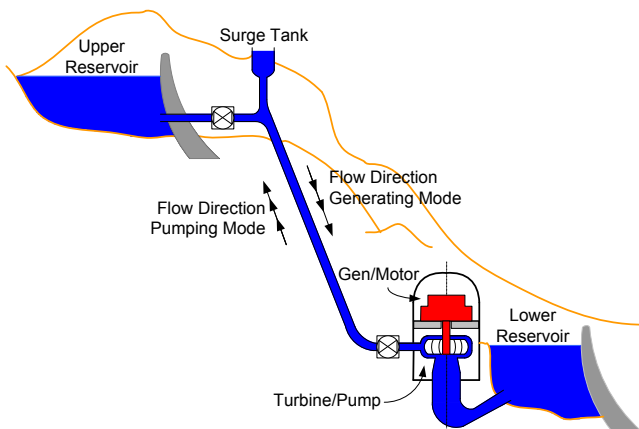


Fig. 1. Pumped storage hydro scheme.

The current round-trip energy efficiency of PSH exceeds 80 percent [1], and primarily for this reason, PSH units have

historically been the only practical method to store and manage large amounts of grid energy. Therefore, they play a vital role in the operation of power systems with a large ingression of renewable energy sources. PSH units can be categorized by prime mover type and by electric machine type. Three basic types of prime mover designs have been employed:

- Units are configured as either dedicated generator/turbine units or dedicated motor/pump units within the same installation.
- Units are configured with a turbine, pump, and generator/motor mounted on the same shaft. These are known as ternary units. They can quickly switch from generator to motor operation without stopping the unit.
- Units are configured as reversible generator/pump units. These units operate in either generating or pumping mode. Switching from generating to pumping mode requires the units to be stopped.

In this paper, we focus on fixed-speed reversible generator/pump units. Additional information on protecting pumped storage hydro installations can be found in [2].

Fig. 2 shows a typical PSH protection scheme for a reversible generator/motor configuration using electromechanical (E/M) relays.

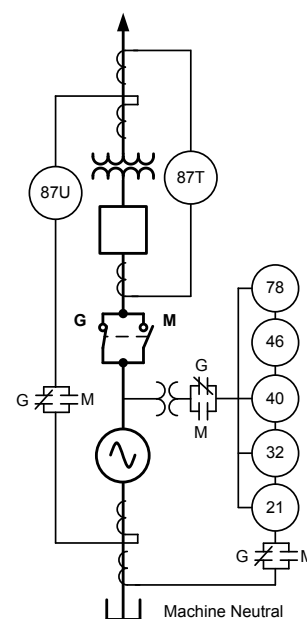


Fig. 2. E/M relays and CT/PT secondary switching.

The primary circuit contains a set of parallel, interlocked switches between the generator breaker and the generator. On the blade-side of the switch (that part of the switch facing the machine) the phasing is swapped. Depending on which switch is closed, G (generating) or M (motoring), the downstream phasing changes from ABC to ACB. For the remainder of the paper, we call this pair of switches the reversing switch. Note that the reversing switch introduces the possibility of a phase-to-phase fault at the machine terminals for the case that both Switches G and M close simultaneously.

Note that the reversing switch is included in the overall unit differential zone (87U). A set of auxiliary contacts in the 87U secondary wiring replicates the position of the reversing switch. These switches transpose the secondary wiring in the same manner as the reversing switch to maintain the correct phase relationship for the 87U. A similar situation exists for the protection elements fed from the machine neutral CT. Some of these elements, for example the machine unbalance element (ANSI 46), respond to a negative-sequence current component. Therefore, a second set of auxiliary contacts are required to ensure that the phase sequence of the currents is correct. A third set of auxiliary contacts ensures the correct phase relationships between the secondary voltages and currents.

2 Impact of the reversing switch on protection functions

From Section 1, we see that the reversing switch can change the phase relationship within the 87U zone and the phase sequence of the protection elements supplied by the machine neutral CTs. The phase relationship change can be addressed by inserting auxiliary contacts that transpose the secondary CT wiring. However, most protection engineers would prefer to avoid inserting auxiliary devices within the CT secondary circuit since it introduces complexity and a point of potential failure in the scheme. Furthermore, failure of the auxiliary device could result in the CTs open circuiting and creating a safety hazard for personnel.

Using the following examples, we show how using digital protective relays addresses the above problems and concerns without switching the secondary wiring of the CTs and PTs.

A typical digital relay has the following capabilities:

1. The differential zone can be dynamically reconfigured to add and remove an input (terminal) to the zone.
2. The phase-rotation setting of the relay can be changed dynamically from ABC to ACB. (This setting determines how sequence quantities are calculated internally.)

The example shown in Fig. 3 uses separate breakers to operate the machine as a generator or a motor (see [2] for other configurations). The primary phasing downstream of Breaker G is transposed, as denoted with a **T**. The transformer differential element (87T) is secure since transposition occurs outside of its zone; however, transposition of the secondary wiring of the generator differential element (87G) is required

(also shown by a **T**). Since both Breakers G and M employ dedicated CTs, no CT switch (external or internal) is required. The generator relay protection elements (excluding the 87G) are denoted by an asterisk (*). The generator relay needs to dynamically change its phase rotation (denoted by a **P**) based on a status indication of Breakers G and M in order for the differential element to remain stable and correctly calculate the voltage and current sequence quantities.

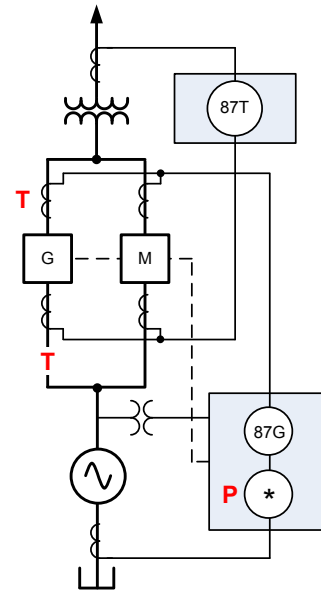


Fig. 3. Individual breakers and CTs.

An alternative strategy to provide protection for PSH is shown in Fig. 4. In this instance, a digital relay provides protection for both the generator and the generator step-up transformer (GSU). The digital relay has the capability to transpose each current and voltage input in the relay. In this sense, it is analogous to the E/M scheme shown in Fig. 2. The pumped storage logic in a particular digital relay uses several settings to configure the logic. These settings specify:

- *The terminal current and voltage inputs to be transposed.* The current and voltage terminals that require transposition are downstream from the reversing switch.
- *The phase pair to be transposed AB, BC, or CA.* This setting transposes the corresponding voltage and current phase pair in software. The software phase transposition occurs early in the data acquisition sequence so that the transposition is transparent to the differential element and sequence calculations. This setting obsoletes the dynamic phase-rotation setting.
- *When to transpose the current and voltage inputs.* This setting is driven from a digital input, which in turn is driven from the reversing switch.

Both the E/M and digital schemes make use of the reversing switch status to adapt the protection for each mode of operation. Therefore, the security of the entire protection scheme depends on the integrity of the status indication. Consequently, we recommend, at a minimum, that dual status indications be used to derive the operating mode. Since the

operating mode cannot change when the unit is online, machine current can be used to further secure the element.

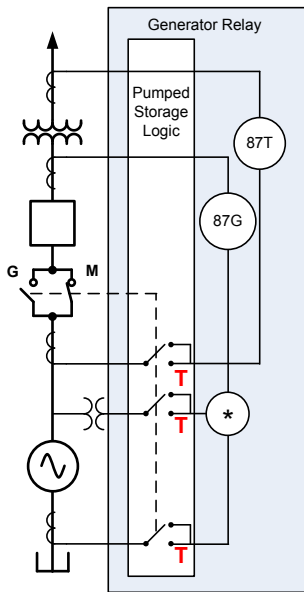


Fig. 4. Relay with integrated pumped storage logic.

One example that can be implemented in a digital relay is shown in Fig. 5.

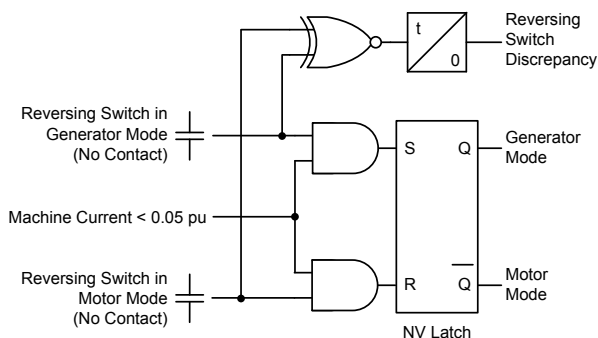


Fig. 5. Operating mode logic.

The logic used to derive the status of the reversing switch shown in Fig. 5 allows the machine to be only in either generator or motor mode. However, should a discrepancy occur due to a problem with respect to the generator or motor breaker auxiliary contacts, it may be possible for both the set (S) and reset (R) inputs of the flip-flop to assert simultaneously. If this should occur, the logic shown in Fig. 5 issues a reversing switch discrepancy alarm. This alarm can be used to take the following corrective actions depending on the magnitude of the machine current.

- If the machine current is above 0.05 pu, the output of the flip-flop will not change state. As such, simply notifying maintenance personnel of the issue is sufficient.
- If the machine current is below 0.05 pu, the output of the flip-flop may toggle—one input typically has priority over the other in the event that both inputs assert simultaneously. Therefore, the case may exist where the wrong operating mode is selected. In this event, the following can be done:

- Allow the differential and other sequence elements to trip the machine in the event that the incorrect operating mode is selected and the machine begins to draw current.
- Block the differential and other sequence element. Once the phase current increases above 0.05 pu of the rated machine current, calculate the positive- (I_1) and negative- (I_2) sequence current magnitudes. If $|I_1| \gg |I_2|$, then the selected or present mode of operation is correct and the differential and other sequence elements can be re-enabled. If $|I_2| \gg |I_1|$, then the selected mode of operation is incorrect. In this situation, the protective relay can select the correct operating mode and re-enable the differential and sequence elements, or the differential elements and sequence elements can remain blocked until the discrepancy is corrected by maintenance personnel.

3 Protection considerations during induction motor starting

One method of starting the synchronous machine when in motor mode is as an induction motor. Since the rotor of a PSH machine is laminated, the damper winding current produces the starting torque of the machine. In contrast, for solid rotor machines (not typically used in PSH applications), the starting torque is developed by the eddy currents, induced on the surface of the pole shoes.

Prior to starting, the field winding is short-circuited via an external resistor to protect the insulation of the field winding and slip rings from abnormally high voltages that are generated in the field before the rotor reaches near synchronous speed [3]. During the machine starting period, the largest portion of the acceleration torque is developed by the damper winding (induction motor effect). This torque accelerates the machine (rotor) to about 95 percent of synchronous speed. At this speed, either the reluctance torque will pull the rotor into synchronism, or more commonly, the field voltage is applied, which will then pull the rotor into synchronism.

In some cases, the supply voltage is reduced during starting. This lowers the starting current, which in turn, reduces the starting torque by the square of the current reduction. This leads to a longer machine starting time. The decrease in the starting current also results in a reduction of the voltage dip in the power system during starting. The voltage reduction is achieved by a specifically designed GSU.

The damper winding is designed to have a high resistance and a low reluctance to obtain the highest ratio of torque to apparent power (MVA) [4]. Not only do the damper windings produce the highest torque during starting, they also experience the greatest thermal increase. Should starting last too long, the damper windings will experience thermal damage. Normally, no water exists in the turbine during starting, but if this is not the case, the load torque could be quite substantial. Therefore, it is important to protect the damper windings of the machine during the starting period. The stator current is relied upon to mimic the heating effect in the damper windings since it's not

possible to directly measure the current in the damper windings.

When E/M relays were applied to PSH units, starting protection was provided either by using a timer interrupted by a speed switch or an overcurrent element with a long timing characteristic [5]. The motor thermal model implemented in digital relays has several advantages over these earlier methods. The thermal model provides thermal protection for both the rotor windings during the starting mode and the stator windings when in the running mode. The thermal model can be configured to account for both the heating and cooling characteristics of the machine. Advanced thermal models derive the slip (s) from the terminal measurements. Using the slip of the machine provides a more accurate heat calculation for high-inertia systems.

In the absence of thermal parameters for the machine, the settings from the existing overcurrent element can be translated into settings for the thermal model. Should the machine's locked rotor current (LRA) and locked rotor time (LRT) be available, we can use these parameters. In this case, the thermal limit can be described by (1).

$$\int I^2 dt = LRA^2 \cdot LRT \quad (1)$$

3.1 Rotor thermal model

The rotor thermal model integrates the motor starting current over time to estimate the thermal capacity used (TCU). For each processing interval (k), a digital relay computes the rotor TCU using (2).

$$TCU[k] = TCU[k - 1] + \Delta TCU[k] \quad (2)$$

where:

$$\Delta TCU[k] = 100 \cdot \frac{\Delta t \cdot I^2[k]}{LRA^2 \cdot LRT}$$

k = present processing interval

$k - 1$ = previous processing interval

Δt = time between two consecutive processing intervals

Note, if the current remains at the LRA magnitude for a duration of LRT, TCU will reach 100 percent after a time equal to LRT. Multiplying and dividing (2) by the rotor resistance (R_r), we obtain (3), the slip-independent thermal model, which we refer to as the I^2t model.

$$\Delta TCU[k] = 100 \cdot \frac{\Delta t \cdot I^2[k] \cdot R_r}{LRA^2 \cdot LRT \cdot R_r} \quad (3)$$

where:

$LRA^2 \cdot LRT \cdot R_r$ = the maximum energy that the rotor can absorb before experiencing thermal damage.

$\Delta t \cdot I^2[k] \cdot R_r$ = the amount of incremental energy accumulated in the rotor during the processing interval.

The slip-dependent thermal model takes into account that R_r is a function of s . To include the dependence of R_r on s , we rewrite (3) as follows:

$$\Delta TCU[k] = 100 \cdot \frac{\Delta t}{LRA^2 \cdot LRT} \cdot \frac{I^2[k] \cdot R_r(s[k])}{R_r(1)} \quad (4)$$

where R_r is a function of s and, $R_r(s)$ is given by:

$$R_r(s) = R_1 s + R_0(1 - s) \quad (5)$$

where:

$$R_1 = R_r \text{ when } s = 1$$

$$R_0 = R_r \text{ when } s = 0$$

$$R_1 \geq R_0 \text{ and } s[k] \in [0,1]$$

Substituting (5) into (4), we obtain (6).

$$\Delta TCU[k] = \frac{100 \cdot \Delta t}{LRA^2 \cdot LRT} \cdot \frac{I^2[k] \cdot (R_1 s[k] + R_0(1 - s[k]))}{R_1} \quad (6)$$

The ratio of $R_1 s[k] + R_0(1 - s[k])$ to R_1 is 1 when $s = 1$, and $0 < \frac{R_0}{R_1} \leq 1$ when $s = 0$. The result now includes the dependence of R_r on s . This allows for a longer starting time than (3), which does not account for the dependence of R_r on s . In Fig. 6, we use data from a 20 MW synchronous motor. Note that while the I^2t model would trip the motor at about 7 seconds, the slip-dependent TCU only reaches a value of 85 percent.

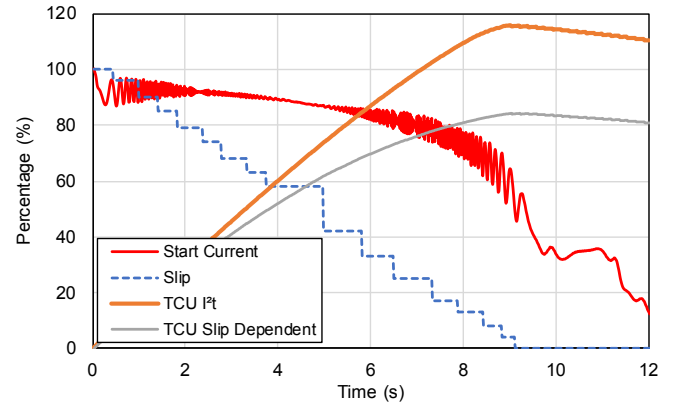


Fig. 6. Slip-dependent vs I^2t thermal model.

4 Dynamic braking

Dynamic braking is installed to enable rapid deceleration and stopping of hydro units that are of the generator and motor combination type (reversible unit). A slow deceleration and stopping of these units results in poor to no lubrication of the bearings for a significant time while the unit decelerates. The rapid deceleration provided by dynamic braking increases bearing longevity. Furthermore, dynamic braking reduces the wobble time of the unit during deceleration. The advantages of dynamic braking over friction braking are as follows:

- Faster decelerating and shorter stopping time,
- No generation of brake dust that will settle in the stator winding and possibly lead to stator winding short circuits.

Dynamic braking is accomplished by short-circuiting the stator windings of the machine once the machine has been isolated from the power grid. The stator windings are shorted via a

normal isolator switch [6]. The rotor circuit is then transferred to a separate dc power supply and excitation maintained until the machine is at a standstill. During dynamic braking, kinetic energy is taken from the rotor of the machine and dissipated as heat in the stator winding, and because the prime mover does not supply energy to the rotor, the rotor begins to slow down. The braking transformer and rectifier are rated to provide nominal stator current (1 pu) during the braking or shorting period. Excitation is maintained until the machine is at a standstill. At standstill, there is still flux in the stator winding, and because the machine is stationary, the stator current begins to decay at a rate determined by the stator L/R ratio. The decaying stator flux generates a voltage that begins to reduce the rotor current since there is an opposing voltage to the applied field voltage. This opposing voltage reduces the effective field voltage across the rotor, which in turn reduces the field current until the stator flux has completely decayed. At this time, the field current increases again. Fig. 7 shows a typical dynamic braking configuration for a reversible unit.

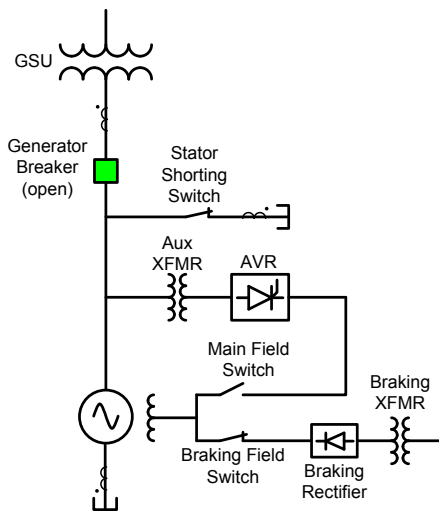


Fig. 7. Typical configuration of a dynamic braking setup for a reversible PSH unit.

4.1 Generator stopping and braking sequence

Following is the operating/switching sequence to decelerate and stop a reversible unit using dynamic braking.

1. Unit is unloaded.
2. Generator breaker opens.
3. Governor stop valve closes.
4. Main inlet valve begins to close, and the unit begins to slow down.
5. Main inlet valve closes completely; this occurs at around 50 percent of rated speed.
6. Main field switch opens.
7. If the excitation system uses a rotating exciter, a wait period is applied to allow the flux in the machine to decay. If the excitation system is static, the excitation switches off when the unit is taken off line.
8. With the main field switch and the generator breaker open, the generator terminal voltage is low; then the stator shorting switch closes.
9. Dynamic braking rectifier turns on, and the dynamic braking field switch closes.

10. Rotor current increases according to the L/R time constant of the rotor circuit.
11. Stator current begins to flow through the stator winding, generating heat due to the winding resistance. As a result, the mechanical kinetic energy stored in the rotor dissipates, and the rotor begins to slow down.

4.2 Protection implications

The stator shorting switch creates a three-phase fault within the generator differential zone. This results in the operation of the generator differential protection. Two options generally exist to avoid the operation of the generator differential under dynamic braking.

4.2.1 Turn off the generator differential

With this option, the generator differential protection is turned off during dynamic braking. The advantage of this method is that it is simple. However, it is not wise to turn off the main generator protection with rated stator current circulating in the stator. This is not the preferred option.

a) Electromechanical schemes

In traditional E/M generator differential schemes, the current inputs short-circuit. In a high-impedance differential scheme, the bus wires short-circuit; whereas for a low-impedance differential generator neutral, the CTs short-circuit.

b) Digital schemes

In a digital generator differential scheme, the operation of dynamic braking will assert a digital input that will disable the generator differential protection.

4.2.2 Add the shorting switch to the differential protection

Another solution is to add the current in the stator shorting switch to the differential circuit, as shown in Fig. 8

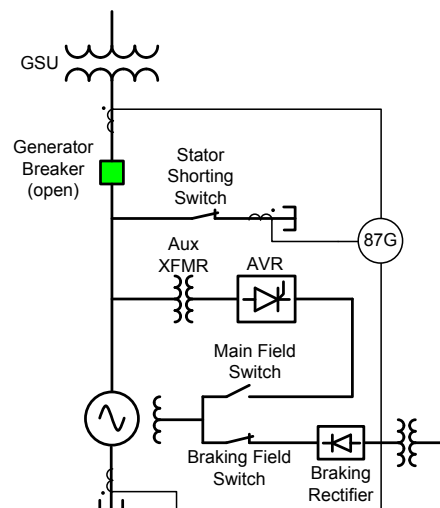


Fig. 8. Dynamic braking differential protection (dynamic braking equipment not shown for clarity).

This stabilizes the differential circuit during dynamic braking; however, it does require a three-input differential scheme with extra CTs.

a) High-impedance schemes

The addition of an extra CT input in a high-impedance differential scheme is simple to implement. The extra is simply connected to the bus wires. However, most high-impedance relays use a tuned circuit in the operating element. This results in a higher operation at lower frequencies and virtually no operation at very low frequencies.

b) Biased differential schemes

E/M biased differential schemes require a three-terminal input relay. Operation at lower frequencies is dependent on the relay design. Digital relays also require a three-terminal input relay. The operation at lower frequencies is dependent on the element design. It may be necessary to disable the generator differential element at frequencies lower than 2.5 Hz.

4.3 Shorting switch and breaker closed

With the addition of the generator shorting switch, a possible new operating problem has been created. Assume the generator is online and an error causes the stator shorting switch to close. The result is a three-phase short circuit within the generator protection zone. Therefore, secure and robust interlocking on the closure of the shorting switch is required. However, shorting switches have closed due to leaks in the pneumatic system. With a CT monitoring the current through the shorting switch, the generator differential protection will remain stable for such events. To provide protection for the unit for the situation in which the generator breaker and the shorting switch are closed simultaneously, an instantaneous overcurrent element (50) is added to the protection scheme to monitor the current through the stator shorting switch, as shown in Fig. 9. The pickup of the overcurrent element is typically set at 1.5 times the rated current of the generator. During dynamic braking, the current magnitude does not exceed the rated current of the generator.

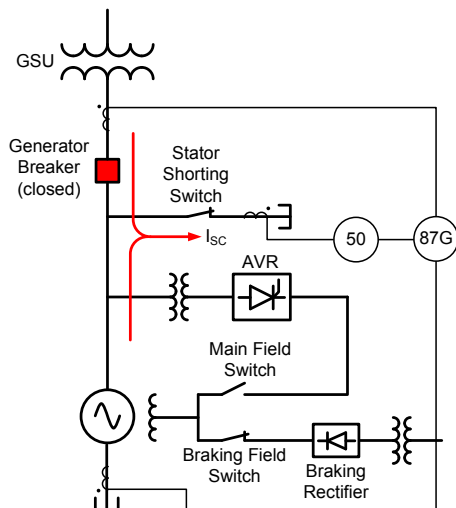


Fig. 9. Dynamic braking overcurrent protection.

For the situation where the generator breaker and stator shorting switch close simultaneously, the fault current through the stator shorting switch will be high enough to operate the overcurrent element (50) and trip the generator breaker. This system is the preferred protection option.

A digital differential relay can provide another option. If the generator breaker closes ($52A = 1$), a digital input in the relay asserts, which in turn removes the shorting switch current input from the differential element. Therefore, should the stator shorting switch close at the same time as the generator breaker, the differential element will no longer be stable and will trip the generator breaker. This is a more elegant solution.

5 Conclusions

Pumped storage hydro reversible units pose a challenge to electromechanical protection schemes. The schemes require either auxiliary contacts to transpose the secondary CT leads or a multiterminal differential protection device to correctly address the instance when the primary phases are transposed as the unit switches from generation into pumping mode. Furthermore, when the unit is started, either back-to-back or using a variable-frequency drive, a relay that does not track frequency cannot adequately protect the unit during the starting period. Digital protective relays track frequency over a wide range, thereby protecting the PSH unit over a wider frequency range. The flexibility and adaptability of digital relays allows them to be easily adapted to any protection scheme.

6 References

- [1] M. Manwaring, D. Mursch, and K. Tilford, "Challenges and Opportunities for New Pumped Storage Developments," *NHA Pumped Storage Development Council*. Available: http://www.hydro.org/wp-content/uploads/2014/01/NHA_PumpedStorage_071212_b12.pdf.
- [2] T. Foxcroft, N. Fischer, D. Finney, R. Chowdhury, M. Donolo, and D. Taylor, "Leveraging Digital Relays for Protection of Pumped Storage Hydro," proceedings of the 44th Annual Western Protective Relay Conference, Spokane, WA, October 2017.
- [3] C. C. Mi, Y. Li, and H. Karmaker, "Modeling of the Starting Performance of Large Solid-Pole Synchronous Motors Using Equivalent Circuit Approach," *IEEE Transactions on Magnetics*, Vol. 45. No. 12, December 2009, pp. 5399–5404.
- [4] T. C. McFarland, "Alternating Current Machines," *D. Van Nostrand Company, Inc.*, January 1949.
- [5] M. Donolo, V. Yedidi, S. Patel, and P. Donolo, "Performance of Synchronous Motors – Loss-of-Synchronism Protection," PCIC 2017.
- [6] F. Jebali and K. Garg, "High-Inertia Synchronous Motor Protection and Lessons Learned," proceedings of the 41st Annual Western Protective Relay Conference, Spokane, WA, October 2014.