GSUT Differential Protection in PSPS

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SIPROTEC 5 Application

GSUT Differential Protection in PSPS

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1 GSUT Differential Protection in PSPS

1.1 Introduction

Pumped storage power stations (PSPSs) are installed to support the power grid with reactive power balance (voltage stabilization) and active power balance (frequency stabilization) based on grid demand. Different to conventional power stations, PSPS has various operation modes, e.g., outputting or intaking active power and reactive power.

The change of operation modes causes the state changes of primary equipment, which lead to a complex protection configuration. The differential protection (ANSI 87T) of the generator step-up transformer (GSUT) is largely influenced by these various operation modes.

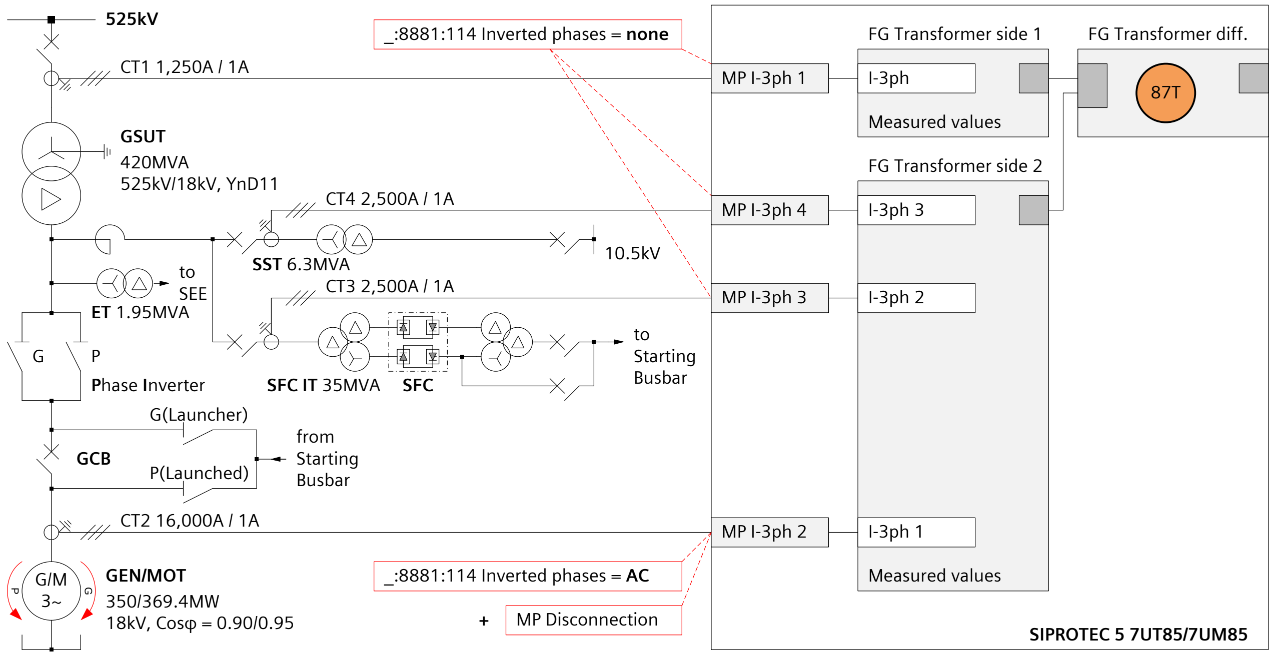
This paper is made based on SIPROTEC 5 V8.30.

1.2 Generator/Motor-transformer Unit in PSPS

General description

The following Figure 1 shows the typical primary diagram for generator/motor-transformer unit in PSPS. The significant differences compared to conventional power station are the installed Phase Inverter between the generator circuit breaker (GCB) and GSUT, and the Starting Busbar.

The GSUT protection device (e.g., 7UT85 or 7UM85) connects all four current transformers of both sides. Various operation modes have different impact on current input MP I-3ph 2. This must be taken into specific consideration of differential protection (ANSI 87T).



GSUT: generator step-up transformer; ET: excitation transformer; SST: station service transformer; SFC: static frequency converter; SFC IT: SFC incoming transformer; GCB: generator circuit breaker; GEN/MOT: synchronous generator/motor

Figure 1: Overview of Connection Diagram of GSUT Differential Protection in PSPS

The synchronous machine GEN/MOT can work as a generator with phase rotation ABC ("G": generating rotation, clockwise direction referred to Figure 1) to output active power to the grid, or work as a motor with phase rotation ACB ("P": pumping rotation, counter-clockwise direction referred to Figure 1) to pump up water, with intaking active power from the grid.

If GEN/MOT is to work as motor, it must be started-up via Starting Busbar powered by a static frequency converter (SFC) or another generator in BtB (back-to-back) Launcher running through the whole frequency band from 0Hz to nominal value (50Hz/60Hz). In this case, the starting current with varying frequency from SFC or BtB Launcher is injected to machine's stator and gradually speeds up the motor till to the rated value (see Figure 14: GEN/MOT X (motor) is started by GEN/MOT (generator)).

The changeover of the phase rotation of a synchronous machine is realized by a so-called Phase Inverter. Phase rotation can be implemented by inverted phases of AB, BC or AC. The description in this paper is based on inverted phases of AC.

Two disconnectors assigned with "G"(generating) and "P"(pumping) in parallel are respectively connected to phase A and C. There are three possible positions for the disconnectors dependent on the GEN/MOT modes,

- For generator mode (generating rotation), G-disconnectors of phase A and C together with phase B disconnector are closed, the others remain open;
- For motor mode (pumping rotation), P-disconnectors of phase A and C together with phase B disconnector are closed, the others remain open;
- In standstill or BtB Launcher (GSUT intaking), all five disconnectors are open;

Please refer to the below diagram.

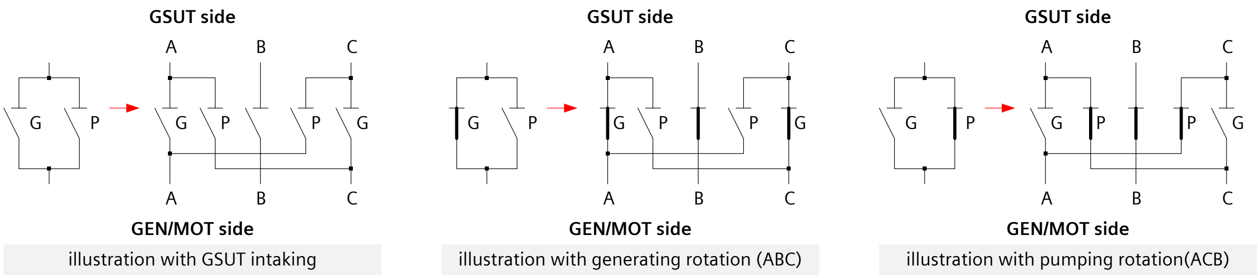


Figure 2: Phase Inverter in Detail

We can see the impact to current input MP I-3ph 2 in case of operation modes changeover as below,

- The phasors of $\underline{I}A$ and $\underline{I}C$ are inverted in case of P position(pumping rotation) of Phase Inverter;
- The measured current is featured by varying frequency (0 -> f_n) during the motor starting up and BtB Launcher, and must not be part of GSUT differential protection;

GSUT differential protection must be prepared for the above explained operation modes. Two specific functions, Phase Sequence Reversal and Measuring Point (MP) Disconnection are designed for this application.

Phase Sequence Reversal

In Figure 2 we see, the primary phasors of $\underline{I}A_{prim}$ and $\underline{I}C_{prim}$ of MP I-3ph 2 are inverted if the Phase Inverter is in position P, whereas the other measuring points MP I-3ph 1, MP I-3ph 3 and MP I-3ph 4 always remain the same. Differential protection makes the calculation phase by phase. To ensure the correct calculation of the differential protection, the device must know, that the primary phasors of $\underline{I}A_{prim}$ and $\underline{I}C_{prim}$ of MP I-3ph 2 arriving at MP I-3ph 2 are inverted.

This can be done by a simple CFC as below,

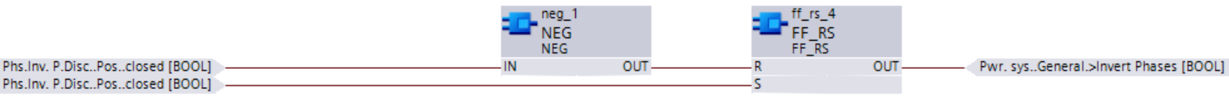


Figure 3: Implemented CFC to Invert the Phase Sequence

To be noted that, we must not invert the phase sequence of all measuring points.

Since we need only to invert the phases of MP I-3ph 2, we must set the parameter "_:8881:114 Inverted phases" to "AC" in the settings only for this MP. For all the other MP the corresponding setting must remain at "none". To activate the phase sequence reversal of selected measuring point MP I-3ph 2, we activate the binary input ">Invert Phases" via CFC as below,

Pwr. sys.	11		*
General	11.2311		*
>Phs-rotation reversal	11.2311.500	SPS	
>Invert Phases	11.2311.501	SPS	X

Figure 4: Activate the Phase Sequence Reversal of Selected Measuring Points

Please note that the change in the phase sequence is only executed if the measurands at the measuring points that are to be switched are under 5% of the rated values.

MP Disconnection

In case of motor starting-up, GEN/MOT(working as motor) intakes the power via Starting Busbar and begins to speed up till to rated value.

In case of BtB Launcher, GEN/MOT(working as generator) outputs power via Starting Busbar to the starting up motor.

In both cases, GSUT is disconnected from GEN/MOT, but there is a measured current with varying frequency at MP I-3ph 2. This measured current must be disconnected from GSUT differential protection.

On the other hand, GEN/MOT will be connected to GSUT via a paralleling device(e.g., 7VE) after the completion of motor starting up. This means that the measured current at MP I-3ph 2 must be reconnected to GSUT differential protection again.

The disconnection and reconnection of MP I-3ph 2 are done by the function “Disconnection of Measuring Points” (available with SIP5 V8.30 and higher versions). Please refer to below configuration,

MP I-3ph 2	11.932		*
Brk.wire det.	11.932.5581		
Supv. balan. I	11.932.2491		
Supv. ph.seq.I	11.932.2551		
Supv. sum I	11.932.2431		
Supv.ADC sum I	11.932.2401		
Saturat. det.	11.932.17731		
CT 3-phase	11.932.8881		*
>Disc. on	11.932.8881.500	SPS	X
>Disc. off	11.932.8881.501	SPS	X
Disconnection	11.932.8881.308	SPC	
Disconnection via BI	11.932.8881.322	SPS	
Disconnect. via control	11.932.8881.324	SPS	

Figure 5: Configuration of the Function MP Disconnection

Special attention must be paid to the setting of this function. When GEN/MOT is reconnected to GSUT after the completion of motor starting up, there is current flow at the moment of GCB closing. So, if we want to reconnect MP I-3ph 2 to GSUT differential protection, we must de-activate the current check criteria of MP Disconnection. Remark: For a short moment (some seconds) after GCB is closed, the starting system will be shut down. During this short period, there is still a current flowing via the Starting Busbar which is seen as a differential current. In order not to trip, the setting for the GSUT differential protection is normally set to such a value that this current does not lead to a pickup.

MP disconnection

11.932.8881.173 Current check: inactive (options: inactive, active)

Figure 6: Setting of the Function MP Disconnection

Below is the reference logic to disconnect and reconnect MP I-3ph 2.

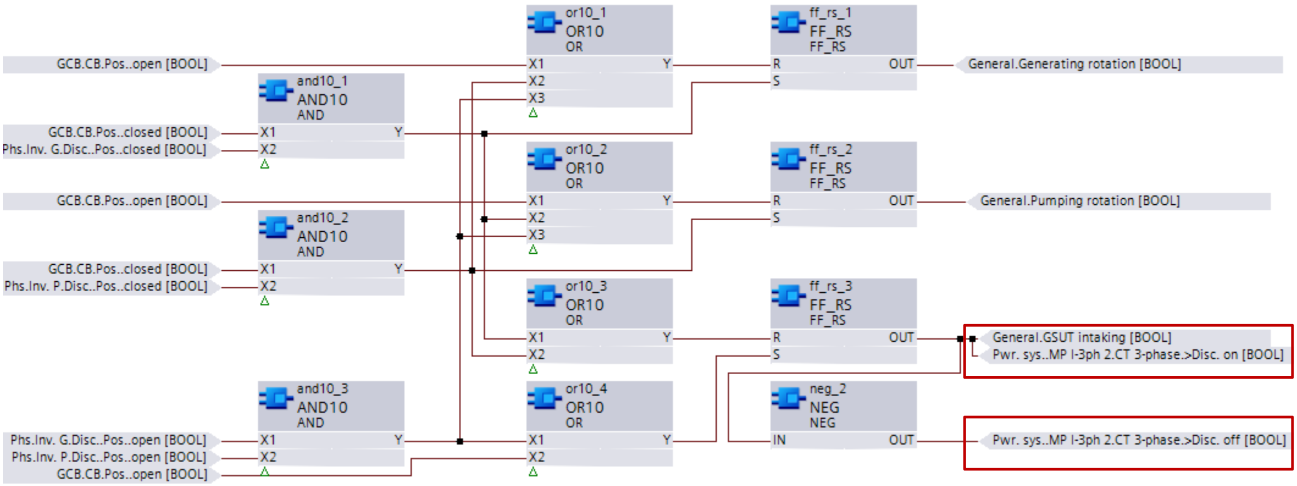


Figure 7: Implemented CFC to Disconnect and Reconnect MP I-3ph 2

If either the GCB or the Phase Inverter (both “G” and “P” disconnectors) is open, the measuring point MP I-3ph 2 is disconnected. If both the GCB and the Phase Inverter (at least one of “G” and “P” disconnector) are closed, the measuring point MP I-3ph 2 is reconnected.

1.3 GSUT Differential Protection under Generating Rotation

Figure 8 shows the schematic connection diagram of GSUT differential protection under generating rotation. The secondary currents injected into GSUT differential protection are also illustrated with the rated operation condition.

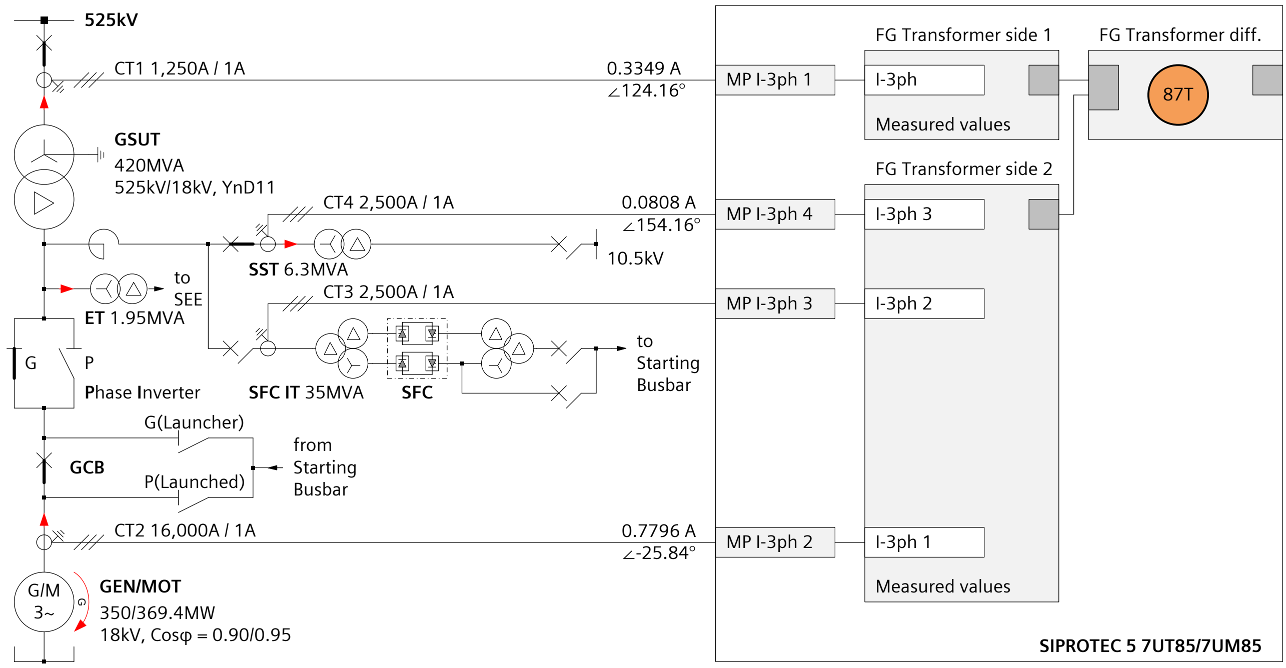
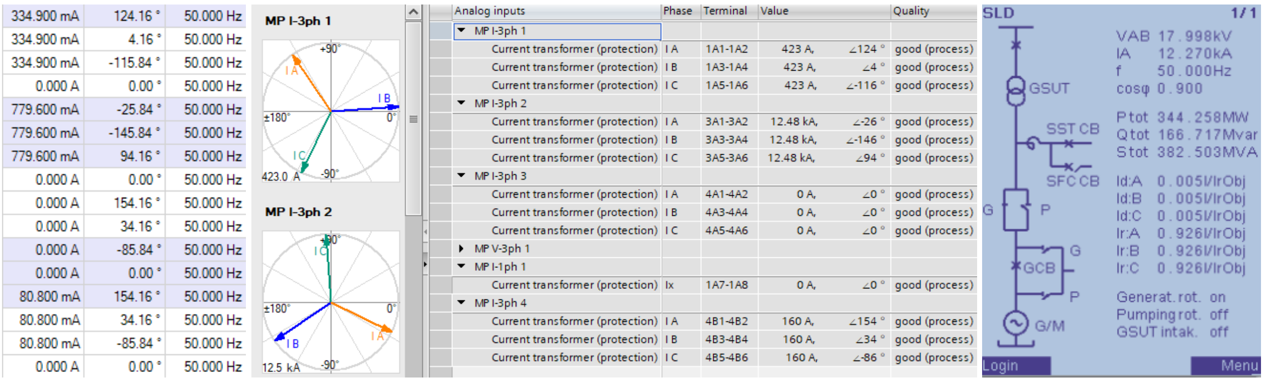


Figure 8: Connection Diagram of GSUT Differential Protection under GEN/MOT Generating Rotation

Under generating rotation, GEN/MOT(working as generator) outputs active power to grid via GSUT, or intakes active power as of generator condenser. GCB and G-disconnector of Phase Inverter are closed, meanwhile P-disconnector is open. All currents to measuring points have the same clockwise phase sequence ABC.

Figure 9 shows the testing result under the rated operation condition as of generator.



A: Injected values B: Measured values C: Display

Figure 9: Testing Illustration of Generating Rotation

The relay shows that Side 2 currents are lagging by 150°, indicating a transformer vector group of 11, which corresponds to the given data in Figure 8.

There can be some differential current seen under rated operation condition. This is caused by the current from excitation transformer (ET) which is not considered into the GSUT differential protection. The differential current can be calculated by the following equation,

$I_d(I/I_{rObj})$ = 1.95 MVA/420 MVA = 0.0046 -> 0.005

This un-balance is always there but so small that it doesn't lead to a picking up of the GSUT differential protection.

1.4 GSUT Differential Protection under Pumping Rotation

Figure 10 shows the schematic connection diagram of GSUT differential protection under pumping rotation. The secondary currents injected into GSUT differential protection are also illustrated with the rated operation condition.

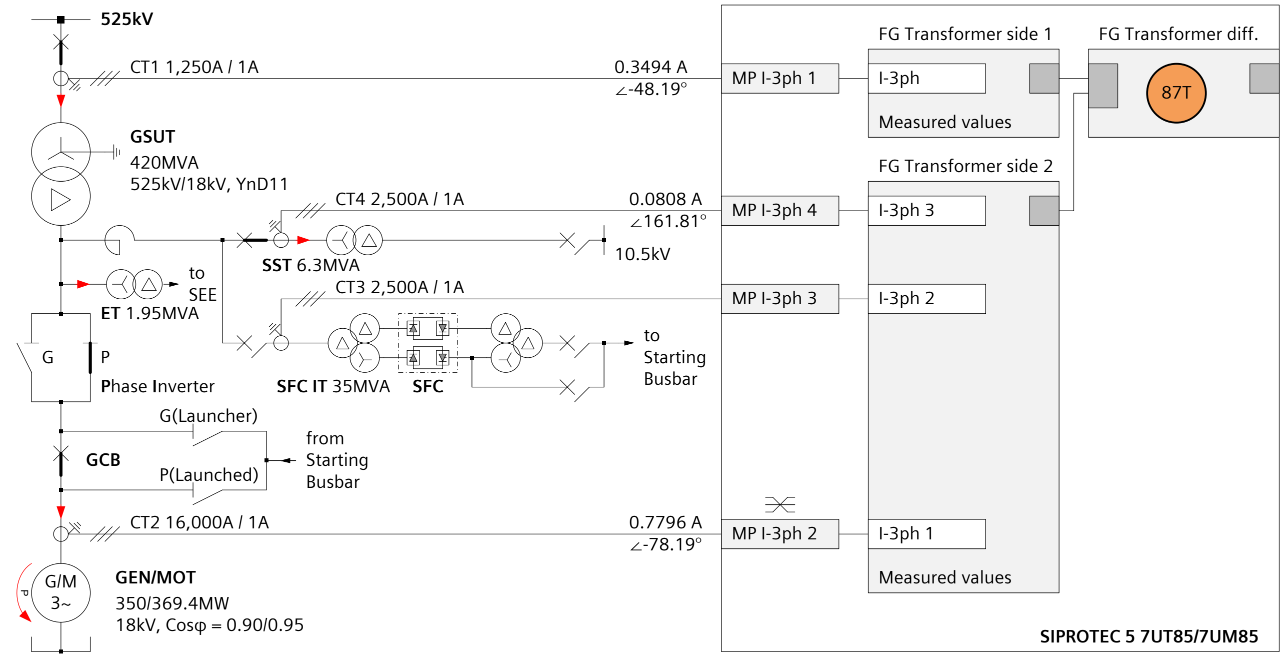
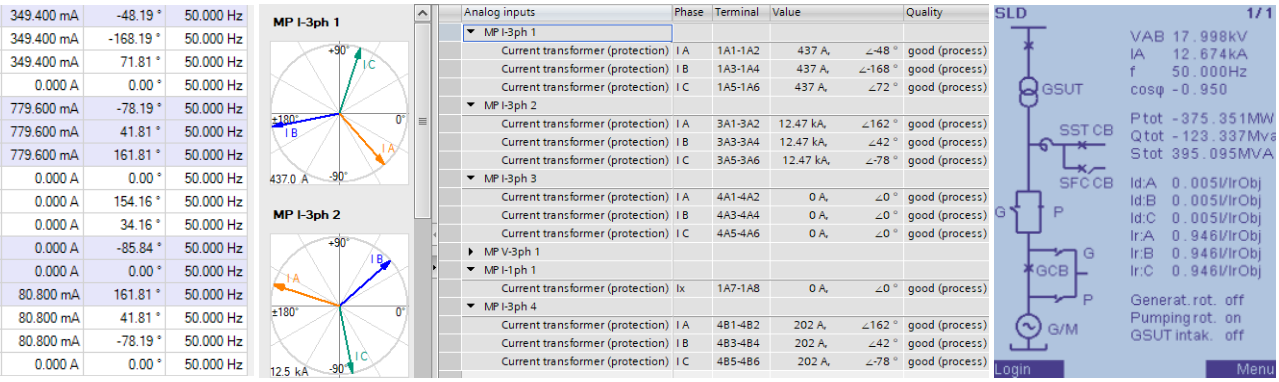


Figure 10: Connection Diagram of GSUT Differential Protection under GEN/MOT Pumping Rotation

Under pumping rotation, GEN/MOT(working as motor) intakes active power from the grid via GSUT. GCB and P-disconnector of Phase Inverter are closed, meanwhile G-disconnector is open. The current from CT2 to measuring point MP I-3ph 2 has a counter-clockwise phase sequence ACB.

According to Figure 3 and Figure 4, the phase sequence of MP I-3ph 2 is inverted by the function Phase Sequence Reversal. This ensures the proper behavior of GSUT differential protection.

Figure 11 shows the testing result under the rated operation condition as of motor.



349.400 mA	-48.19 °	50.000 Hz
349.400 mA	-168.19 °	50.000 Hz
349.400 mA	71.81 °	50.000 Hz
0.000 A	0.00 °	50.000 Hz
779.600 mA	-78.19 °	50.000 Hz
779.600 mA	41.81 °	50.000 Hz
779.600 mA	161.81 °	50.000 Hz
0.000 A	0.00 °	50.000 Hz
0.000 A	154.16 °	50.000 Hz
0.000 A	34.16 °	50.000 Hz
0.000 A	-85.84 °	50.000 Hz
0.000 A	0.00 °	50.000 Hz
80.800 mA	161.81 °	50.000 Hz
80.800 mA	41.81 °	50.000 Hz
80.800 mA	-78.19 °	50.000 Hz
0.000 A	0.00 °	50.000 Hz

Analog inputs	Phase	Terminal	Value		Quality
MP I-3ph 1					
Current transformer (protection)	I A	1A1-1A2	437 A,	∠-48 °	good (process)
Current transformer (protection)	I B	1A3-1A4	437 A,	∠-168 °	good (process)
Current transformer (protection)	I C	1A5-1A6	437 A,	∠72 °	good (process)
MP I-3ph 2					
Current transformer (protection)	I A	3A1-3A2	12.47 kA,	∠162 °	good (process)
Current transformer (protection)	I B	3A3-3A4	12.47 kA,	∠42 °	good (process)
Current transformer (protection)	I C	3A5-3A6	12.47 kA,	∠-78 °	good (process)
MP I-3ph 3					
Current transformer (protection)	I A	4A1-4A2	0 A,	∠0 °	good (process)
Current transformer (protection)	I B	4A3-4A4	0 A,	∠0 °	good (process)
Current transformer (protection)	I C	4A5-4A6	0 A,	∠0 °	good (process)
MP V-3ph 1					
MP I-1ph 1					
Current transformer (protection)	Ix	1A7-1A8	0 A,	∠0 °	good (process)
MP I-3ph 4					
Current transformer (protection)	I A	4B1-4B2	202 A,	∠162 °	good (process)
Current transformer (protection)	I B	4B3-4B4	202 A,	∠42 °	good (process)
Current transformer (protection)	I C	4B5-4B6	202 A,	∠-78 °	good (process)

A: Injected values B: Measured values C: Display

Figure 11: Testing Illustration of Pumping Rotation

It's obviously seen that the measured phase sequence(ABC) of MP I-3ph 2 is inverted compared to the injected values(ACB). GSUT differential protection now works well.

1.5 GSUT Differential Protection under GSUT Intaking

If GCB is open, or both G-disconnector and P-disconnector of Phase Inverter are open, GSUT is galvanically isolated from GEN/MOT, and intakes active power from the grid and feeds it into 10.5kV station service system.

GSUT intaking takes place under three primary conditions,

- GEN/MOT standstill;
- Motor starting up;
- BtB Launcher;

GEN/MOT Standstill

Figure 12 shows the schematic connection diagram of GSUT differential protection with GEN/MOT standstill. The secondary currents injected into GSUT differential protection are also illustrated with the rated operation condition.

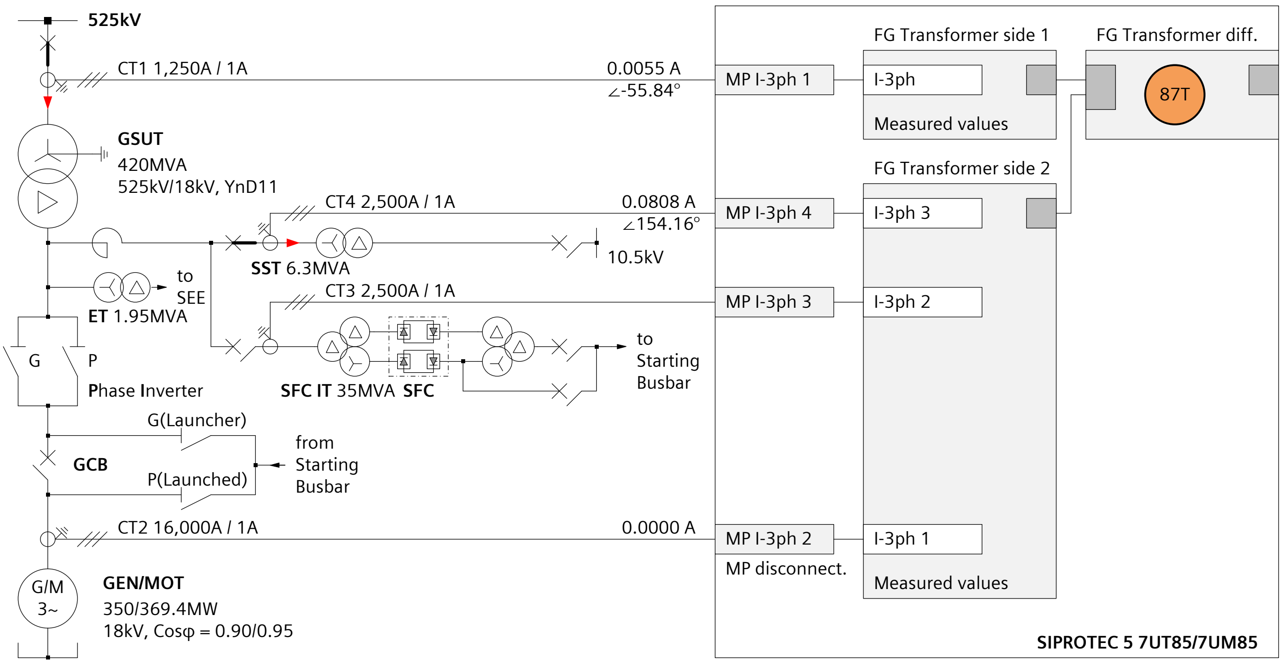


Figure 12: Connection Diagram of GSUT Differential Protection under GSUT Intaking with GEN/MOT Standstill

With GEN/MOT standstill, GSUT intakes active power from grid. All of GCB, G-disconnector and P-disconnector of Phase Inverter are open. The measuring point MP I-3ph 2 has no current.

Motor Starting up

Figure 13 shows the schematic connection diagram of GSUT differential protection with motor starting up. The secondary currents injected into GSUT differential protection are also illustrated with the rated operation condition.

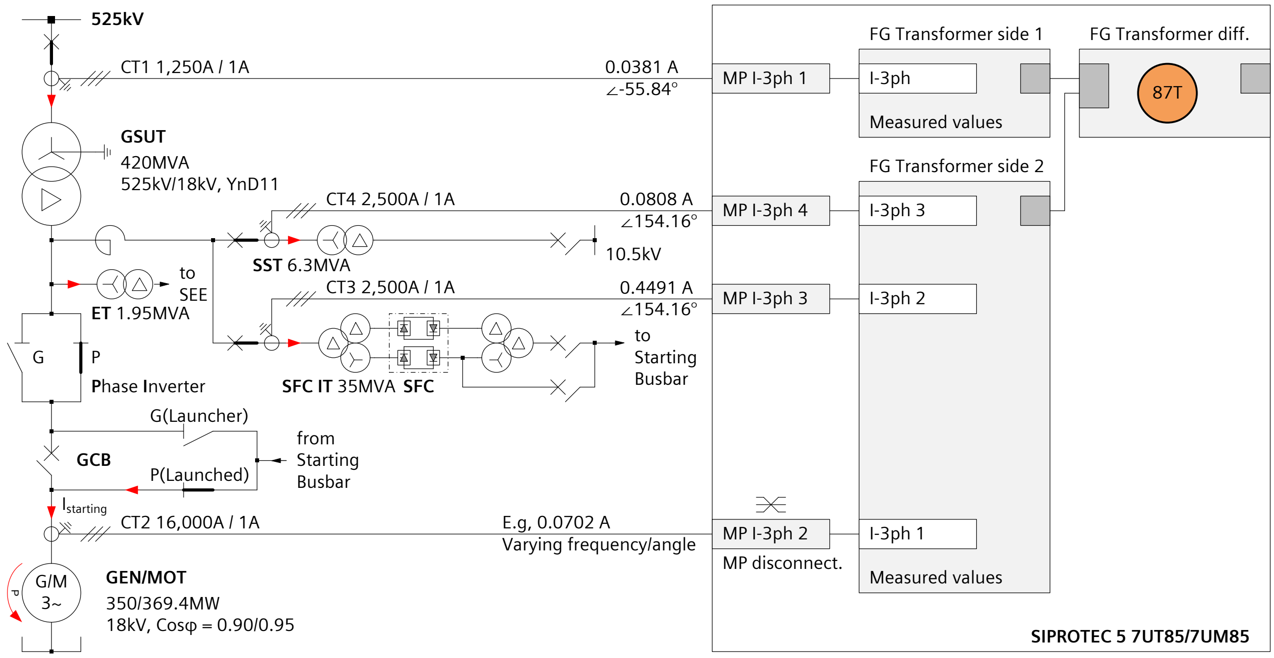


Figure 13: Connection Diagram of GSUT Differential Protection under GSUT Intaking with Motor Starting up

With motor starting up, GSUT intakes active power from grid, GEN/MOT intakes power from SFC or a BtB Launcher via starting busbar and then, gets started up and speeds up till to rated speed. GCB and G-disconnector of Phase Inverter are open, meanwhile P-disconnector is closed. The measuring point MP I-3ph 2 sees a starting up current $\underline{I}_{starting}$ of varying frequency (0Hz~f_n) and counter-clockwise phase sequence ACB.

BtB Launcher

Figure 14 shows the schematic connection diagram of GSUT differential protection with BtB Launcher. The secondary currents injected into GSUT differential protection are also illustrated with the rated operation condition.

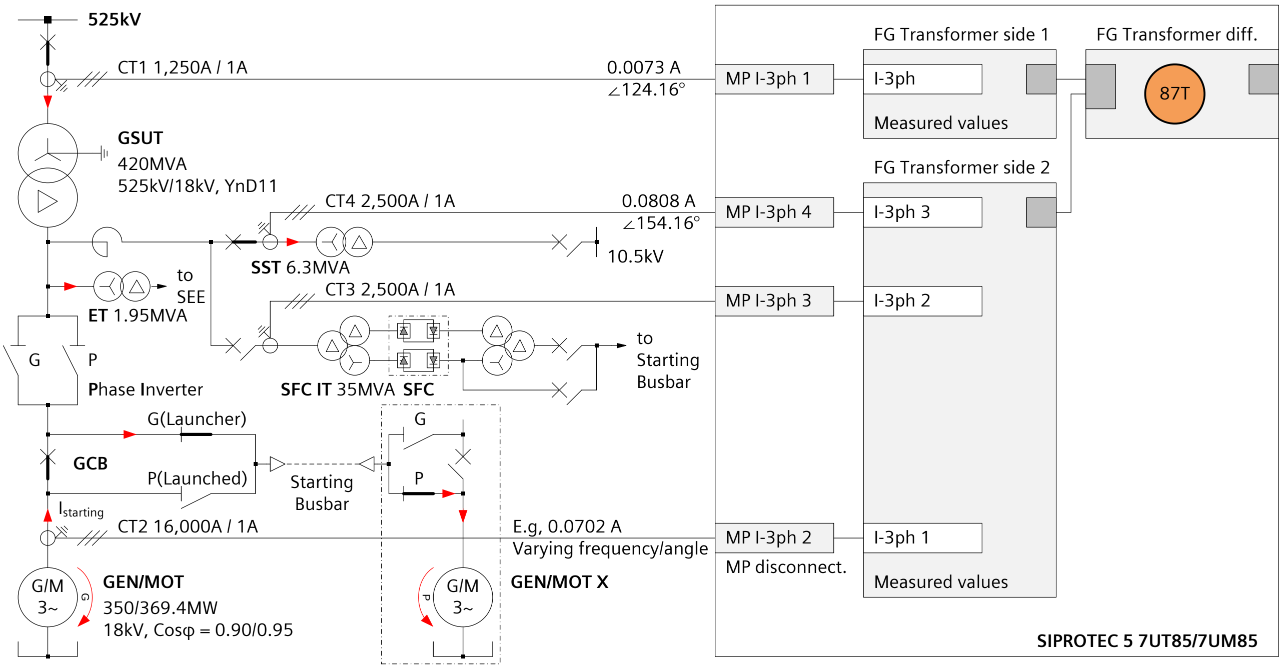
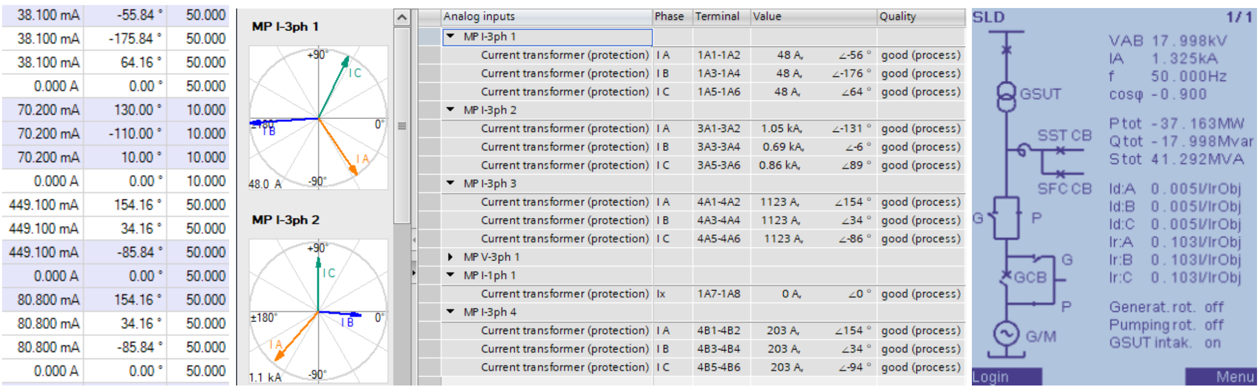


Figure 14: Connection Diagram of GSUT Differential Protection under GSUT Intaking with BtB Launcher

With BtB Launcher, GSUT intakes active power from grid, GEN/MOT outputs power directly to a BtB started motor via starting busbar till to rated speed. GCB is closed, meanwhile both G-disconnector and P-disconnector of Phase Inverter are open. The measuring point MP I-3ph 2 sees a starting up current $\underline{I}_{starting}$ of varying frequency (0Hz~f_n) and clockwise phase sequence ABC.

Testing

Figure 15 shows the testing result of motor starting up under the rated operation condition(assumed 10.00Hz for GEN/MOT).



A: Injected values B: Measured values C: Display

Figure 15: Testing Illustration of GSUT Intaking with Motor Starting up

We can see that the measuring point MP I-3ph 2 is displayed but disconnected from differential calculation. GSUT differential protection works well.

1.6 Additional Frequency Tracking

In Figure 15 we see that the measuring point MP I-3ph 2 shows the wrong measuring values. The secondary injected current of MP I-3ph 2 is 0.0702A, the correct primary measurement should be 1,123.2A(= 0.0702A*16,000A/1A).

The injected frequency is 10.00Hz. This large frequency deviation from the rated value 50.00Hz causes the large measurement error.

The wrong measurement of MP I-3ph 2 has no influence on the differential calculation because this measuring point is disconnected. But, if you want to implement a protection function, e.g., over-current, with measuring point MP I-3ph 2, you must correct the measurement.

This can be done by an additional measuring point of the SIPROTEC 5 device, a separate FG(function group) and an additional frequency tracking group.

Frequency Tracking

SIPROTEC 5 devices are equipped with powerful sampling-frequency tracking to ensure high measuring accuracy over a wide operating range(10Hz~90Hz).

A default frequency tracking group with ID number 1 is standardized to all SIPROTEC 5 device. This is enough if all measuring points in a system are galvanically coupled to each other, the power frequency is identical for all measuring points.

There are problems with system states where galvanically separation is possible and measuring points of the separated system parts are connected to the same SIPROTEC 5 device. For these problematic system states, different frequencies are possible for a limited time. Depending on the measuring point set for tracking, the device selects which frequency to use. As a result, measuring errors and a failure of protection functions are possible.

All measuring points connected to one FG must have the same frequency tracking group ID number. A separated frequency tracking group with different ID number is required for a galvanically separated system.

For GSUT protection in PSPS, the measuring point with CT2 is galvanically separated from other measuring points under GSUT intaking. If some functions(e.g., over-current) have to work with this measuring point, it must work with a separated frequency tracking group to ensure the accurate measurement.

Here, we have a second frequency tracking group AddFrqTrakGr with ID number 2.

Special Wiring and Configuration

Figure 16 shows the schematic connection diagram and the device configuration with motor starting up.

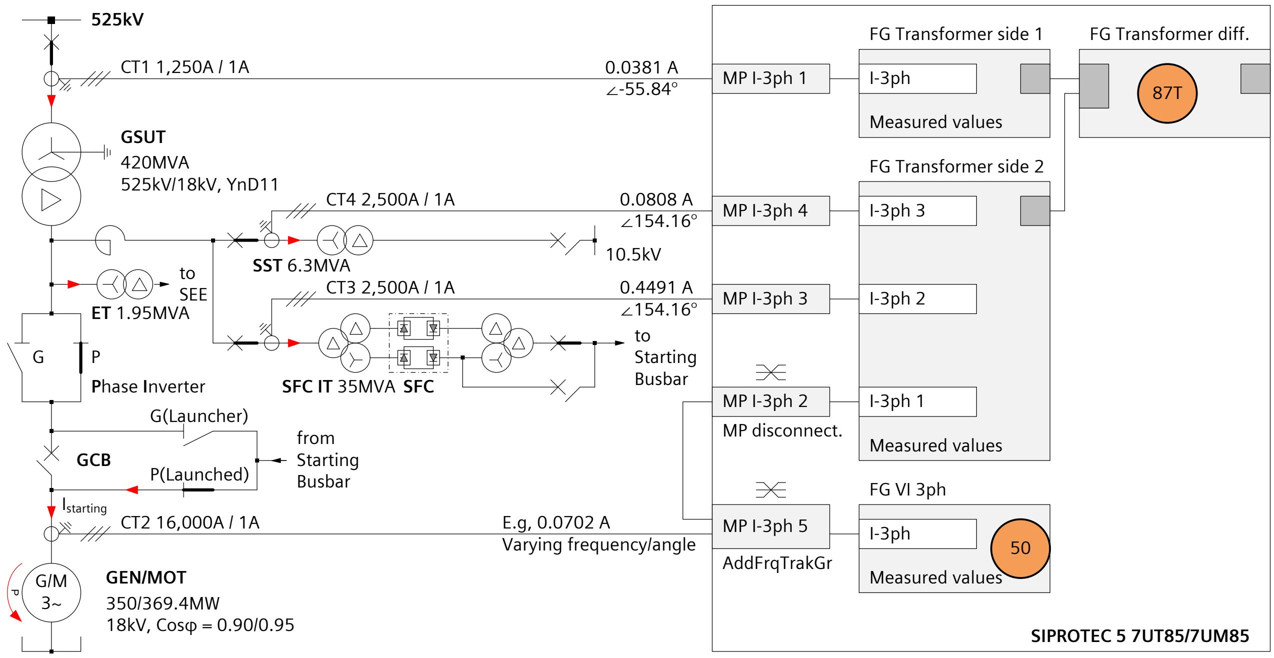


Figure 16: Connection Diagram of Additional Over-current Protection with CT2

SIPROTEC 5 device has an additional measuring point MP I-3ph 5, a separate FG VI 3ph and an additional frequency tracking group AddFrqTrakGr with ID number 2. The current from CT2 is wired to MP I-3ph 2 and MP I-3ph 5 in series. The separate FG VI 3ph (over-current protection included) works with the measuring point MP I-3ph 5.

Both measuring points of MP I-3ph 2 and MP I-3ph 5 must be phase sequence inverted.

All measuring points beside MP I-3ph 5 are assigned to the default frequency tracking group with ID number 1, while MP I-3ph 5 is assigned to frequency tracking group with ID number 2. The routing in the matrix between the measuring points and frequency tracking groups is done as below,

Measuring point	Freq tracking group ID
(All)	(All)
MP I-3ph 1[ID 1]	1
MP I-3ph 2[ID 2]	1
MP I-3ph 3[ID 3]	1
MP V-3ph 1[ID 5]	1
MP I-1ph 1[ID 6]	1
MP I-3ph 4[ID 4]	1
MP I-3ph 5[ID 7]	2
	1
	2

Figure 17: Route Matrix between the Measuring Points and Frequency Tracking Groups

Testing

Figure 18 shows the testing result with additional frequency tracking group.

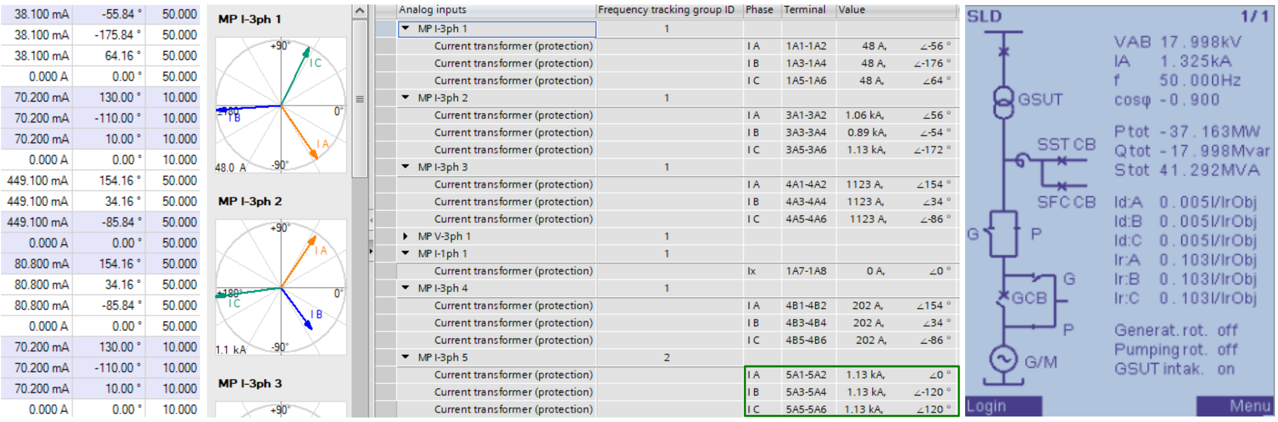


Figure 18: Testing Illustration of Additional MP I-3ph 5

We see that the measuring point MP I-3ph 5 now shows correct measurement values (magnitude and phase sequence), so the over-current protection behaves correctly (green marking).

We can also see the proper measured values of system frequency and tracking frequency of both frequency tracking groups as below.

Measurements	Value	Quality	Number
Function values			
General			
fsys	50.00 Hz	good (process)	11.2311.324
ftrack	50.00 Hz	good (process)	11.2311.325
AddFrqTrakGr			
fsys	10.00 Hz	good (process)	11.19921.322
ftrack	10.00 Hz	good (process)	11.19921.323

Figure 19: Illustration of Both Frequency Tracking Groups

1.7 Paralleling to Power Grid

At the end of motor starting up, the voltage and frequency of GEN/MOT come approximately to rated values. Then, the motor will be brought into synchronous condition and connected to the power grid by a paralleling device. The measured current at MP I-3ph 2 must be reconnected to GSUT differential protection again.

There is power flow at the moment of GCB closing. We must disable the current check criteria of MP Disconnection to ensure the reconnection of MP I-3ph 2 when GCB is closed. As already mentioned, there is an overlapping time where the GCB is already closed, and the Starting Busbar not yet disconnected. The resulting differential current can be seen but doesn't lead to a picking up of the GSUT differential protection.

Anyhow the behavior of GSUT differential protection must be checked during the commissioning of GEN/MOT operation mode's transition.

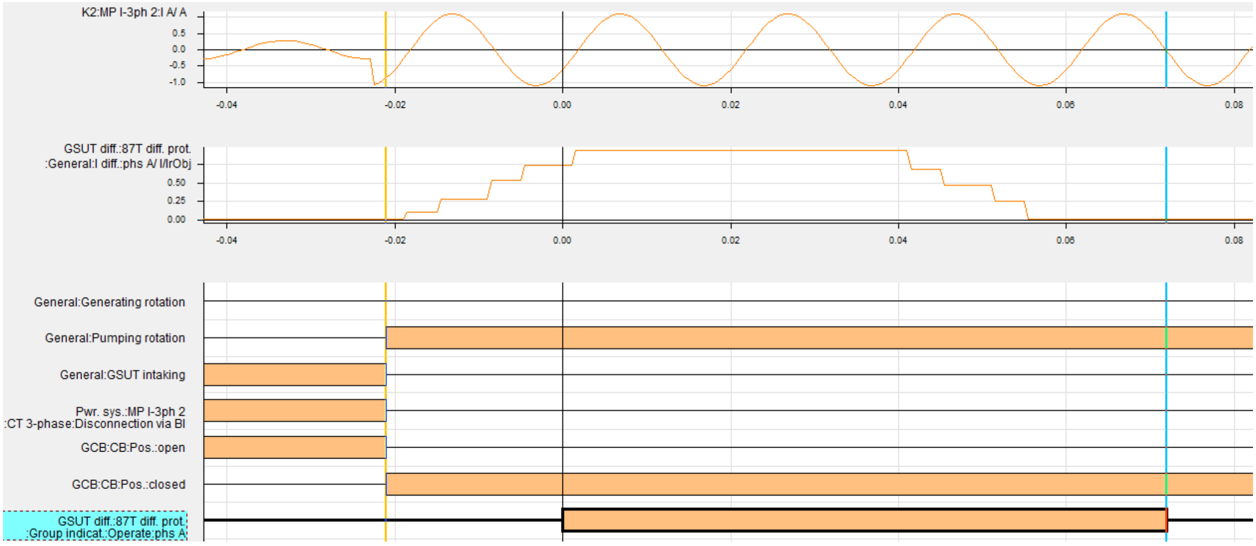


Figure 20: Wrong Picking up of GSUT Differential Protection during the Transition

Above Figure 20 shows an example to check the behavior of GSUT differential protection during the transition. The message “Disconnection via BI” had an immediate drop out after GCB was closed, but GSUT differential protection still picked up for 72ms (the right behavior should be no picking up). It was clarified that the internal drop out delay (3 cycles) of “Disconnection activated” of MP Disconnection logic caused the delayed reconnection of MP I-3ph 2 and then differential current. The stage I-Diff> picked up because the current flow (per unit value) arriving at MP I-3ph 2 at GCB closing instant is larger than the threshold.

After the expiration of internal drop out time delay of “Disconnection activated”, the measuring point MP I-3ph 2 was reconnected again and then the differential protection dropped out.

This wrong picking up must be stabilized for a short time(e.g., 80ms) via an additional CFC logic (refer to Figure 21) after GCB is closed.

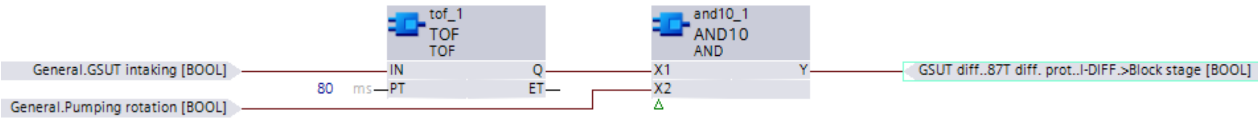


Figure 21: Reference Logic for A Short Blocking

After the completion of GEN/MOT paralleling to grid, GSUT differential protection works with operation mode of pumping rotation.

1.8 Conclusion

GSUT differential protection in PSPS is complex due to the change of various operation modes. Described solutions in this application note shows out a way how one transformer differential protection in SIPROTEC 5 device can be dynamically adapted to all the various operation modes to guarantee a correct behavior.

It is also shown, how galvanically separated system (with different frequency) can be properly handled by SIPROTEC 5 devices.

Thanks to the advanced functions of frequency tracking, phase sequence reversal and disconnection of measuring points, customer will benefit a lot from the mentioned features of SIPROTEC 5.

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Alpharetta, GA 30005
United States

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