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Overall Differential Protection for Pump Storage Power Plant with Tapped-Delta Design of the Unit Transformer

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1 INTRODUCTION

Every pump storage power station has at least three different operating modes which can cause possible challenges during design of the protection scheme. These three operating modes are generating mode, pumping mode and machine starting into pumping mode.

The main differences between the generating and pumping operating modes are changes in direction of the synchronous machine rotation and change of direction (i.e. sign) of the active power flow. This rotation direction change is achieved by so-called phase reversal disconnectors. These disconnectors simply swap two phases in pumping mode in order to reverse the phase sequence to the synchronous machine. However, the physical location of the phase reversal disconnectors can be crucial for proper design of some protection functions (e.g. overall differential protection) for the generator/motor-transformer unit. For this particular installation, phase reversal disconnectors 89G and 89P are located in-between the low-voltage bushings of the unit transformer and the synchronous machine (see Fig. 1 for more details), thus within the protection zones of the overall differential relay.

Machine starting into pumping mode of operation is specific for every pump storage power plant. In this particular station, machine is started as an asynchronous motor by using direct-on line starting method with reduced voltage. Voltage reduction is obtained by a special design of the unit transformer. So-called tapped-delta design, of the unit transformer secondary delta winding, is used (see Fig. 2).

The overall differential protection in any power station application must be based on the ampere-turn balance of the unit transformer. Thus in principle one can say it is a variant of a standard transformer differential protection. In order to provide proper overall differential protection scheme design, for this power plant by using current transformers CT1, CT7 and CT8, as shown in Fig. 1, all of the above factors must be taken into account during protection scheme design. One of the challenges is how to treat the currents from current transformer CT7 (i.e. machine star point) which can be connected in three different ways to the unit transformer depending on active operating mode of the machine. The second challenge is how to select and set the unit transformer rated data (e.g. power, voltage and vector group) for the overall differential protection because of the special design used for this transformer.

This paper will show how the overall differential protection scheme is designed by using modern numerical IED of the latest generation. Adaptive scheme is used with facility for switching of CT7 currents in the relay software.

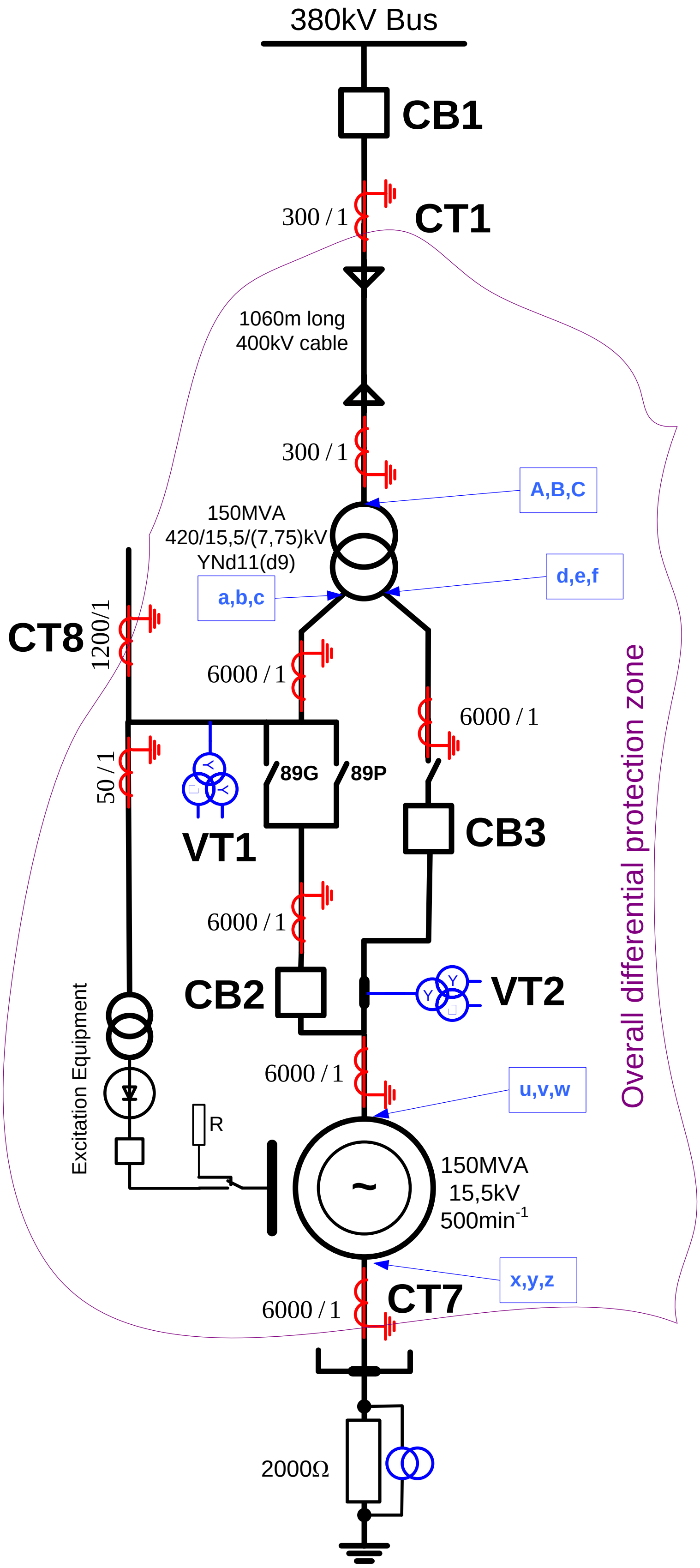


Fig. 1: Power plant single line diagram and bushing designations for machine and unit transformer

2 POWER STATION SETUP

Fig. 1 gives overview of one generator/motor-transformer unit, associated current and voltage instrument transformers with their respective ratios and bushing designations for machine and unit transformer. Location of phase-reversal disconnectors is also shown. This paper will not present the complete protection scheme for this pump storage power plant because such type of information can be found in reference [3] but it will instead describe the challenges faced during design of the overall differential protection for this power plant.

2.1 Unit transformer design

The unit transformer is actually two-winding transformer with vector group YNd11. However, from the middle point of every LV phase connected in delta, three additional bushings "d, e and f" are also made available, as shown in Fig. 2. Such transformer design makes effectively "third phantom winding" with rated voltage 7,75kV and vector group Yd9. Note that data for this "third phantom winding" are given in parenthesis in Fig. 1 and Fig. 2. This "third winding" is only used during machine starting into pumping mode as described in the next section. Thus, for the differential protection this transformer shall be treated as a three-winding YNd11d9 power transformer [4].

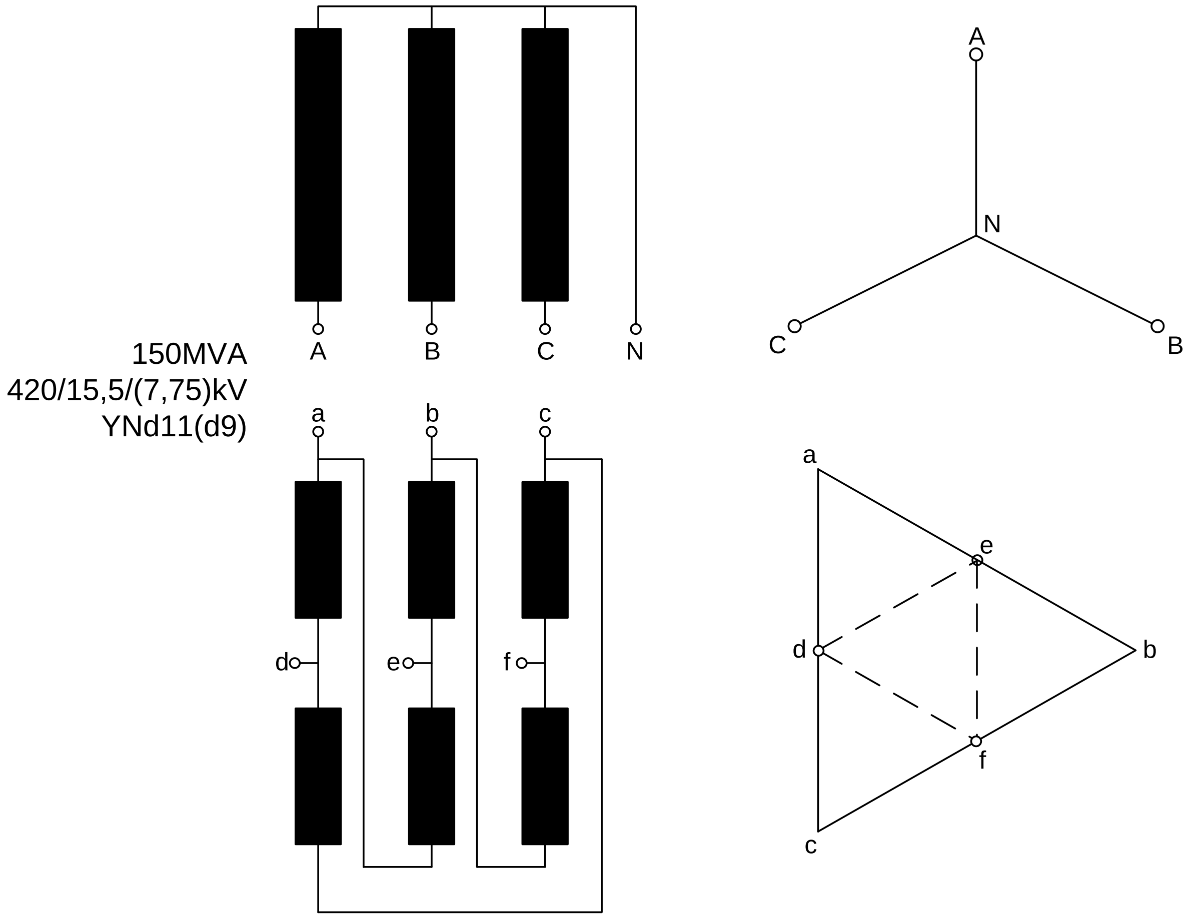


Fig. 2: Unit transformer rating plate information with bushing designations

2.2 Machine starting into pumping mode

In every pump storage power plant, machine starting into pumping mode poses a challenge to the plant designer. Many different solutions are used around the world. In this particular installation, pump is started as an asynchronous motor by using Direct-on-Line (DoL) starting method with reduced voltage. Voltage reduction is obtained by a special design of the unit transformer as explained in the previous section. Thus the pump starting sequence contains the following steps:

- Machine is at standstill

- Unit transformer is energized from the HV system (CB1 is closed, CB2 and CB3 are opened, see Fig. 1 for circuit breaker physical locations)
- By using a compressor water is taken away from the turbine chamber
- Phase reversal disconnector 89P is closed
- Additional starting resistor is inserted in the rotor circuits in order to further reduce machine starting current
- Then CB3 is closed and machine is started as asynchronous motor with DoL method but only at 50% of the rated voltage. RMS value of the machine starting current is around 200% of the rated current. Note that this starting current will be seen by HV network as rated current only (i.e. 100%) due to change of unit transformer ratio during starting.
- When machine accelerates to almost synchronous speed, the starting resistor is disconnected and excitation is applied to the rotor
- Machine is pulled into synchronous motor mode operation, but still at 50% of rated voltage
- Then CB3 is opened and machine is temporarily disconnected from the network
- Excitation is forced during next 1s in order to increase machine terminal voltage from 50% to almost 100%
- After this 1s field forcing, machine is resynchronized to the network by closing CB2
- The pump is loaded by opening the wicket gates

More detailed information about the starting sequence can be found in reference [5].

3 OVERALL DIFFERENTIAL PROTECTION

In any power station application, the overall differential protection must be based on the ampere-turn balance of the unit transformer. Thus in principle one can say it is a variant of a standard transformer differential protection. In order to provide proper overall differential protection scheme design for this power plant, current transformers CT1, CT7 and CT8 shall be used, as shown in Fig. 1. Note that theoretically the 50/1 excitation transformer CT shall also be connected to this scheme, but in practice it can be omitted due to very limited amount of current which will flow at this point.

CT1 and CT8 are connected in a fixed way to the overall differential protection zone. However CT7 (i.e. currents from the machine star point) can be connected in three different ways to the unit transformer depending on active operating mode of the unit (i.e. actual positions of CB2, CB3, 89G and 89P). Possible connections for CT7 are shown in Table 1.

Table 1: Galvanic connections of the machine star point bushings to the unit transformer bushings

	Generating Mode	Pumping Mode	DoL starting
Machine bushing ‘x’ to bushing	a (15,5kV)	c (15,5kV)	f (7,75kV)
Machine bushing ‘y’ to bushing	b (15,5kV)	b (15,5kV)	e (7,75kV)
Machine bushing ‘z’ to bushing	c (15,5kV)	a (15,5kV)	d (7,75kV)

For most numerical differential relays power transformer rating plate data shall be entered in order to balance the transformer differential protection. However what about this application? Which data need to be entered? How CT currents need to be connected to the relay?

It should be known that any power transformer rating plate data (see Fig. 2 for unit transformer rating plate data) are given in respect with its bushing markings. Thus, if currents for the overall differential protection are connected to the differential relay in the same order (i.e. sequence) as bushing markings, the unit transformer rating plate data can be used directly to balance the numerical differential relay. Thus the following shall be done during engineering of the overall differential relay CT connections:

- relay phase currents L1, L2 & L3 for 420kV winding shall be connected as IA, IB & IC

- relay phase currents L1, L2 & L3 for 15,5kV winding shall always be connected as Ia, Ib & Ic
- relay phase currents L1, L2 & L3 for 7,75kV winding shall always be connected as Id, Ie & If

The used numerical overall differential protection relay [1] is adaptive and it can be engineered to switch the CT7 currents towards the overall differential function depending on unit active mode of operation. Note that the CT7 secondary wiring is fixed towards the relay hardware. All necessary re-connections of CT7 currents are performed in the relay software. However, note that all CT7 software current switching will only be performed during periods of time when there are no any stator winding currents in the primary circuit.

Information about generating or pumping mode of operation is given to the relay via two binary inputs from the power plant control system. Information about DoL starting mode is derived within the relay by measuring the machine terminal voltage by using VT2 in pumping mode of operation. If this voltage is low (i.e. below 75%) DoL starting is anticipated and appropriate CT7 connections are made in software. Once the measured voltage increase above 75%, pumping mode of operation is assumed and CT7 currents are switched in software accordingly. Table 2 summarizes CT connection towards the overall differential protection.

Table 2: CT connections to the overall differential protection

	Winding 1 Currents	Winding 2 Currents	Winding 3 Currents
Generating Mode	**CT1:** IL1, IL2, IL3	**CT8:** IL1, IL2, IL3 **CT7:** Ix, Iy, Iz	-
Pumping Mode	**CT1:** IL1, IL2, IL3	**CT8:** IL1, IL2, IL3 **CT7:** Iz, Iy, Ix	-
DoL starting	**CT1:** IL1, IL2, IL3	**CT8:** IL1, IL2, IL3	**CT7:** Iz, Iy, Ix

Table 3: Base data required for overall differential protection setup

	Winding 1	Winding 2	Winding 3
SBase	150 MVA		
UBase	420 kV	15,5 kV	7,75 kV
IBase	206 A	5587 A	11174 A
Vector Group	Y	d11	d9
Zero Sequence Reduction	On	Off	Off

When CT currents are always connected to the differential relay in accordance with the transformer bushing markings, the transformer rated data shall be entered into the relay in order to balance the differential function in accordance to references [1] and [2]. Necessary data for this particular application are shown in Table 3.

Because CT current switching for overall differential protection function is voltage dependent, this function is blocked by VT2 fuse failure signal in the pumping mode of operation.

4 FIELD RECORDINGS

The overall differential protection scheme for the first unit was put in services in June 2010 and for the second unit in November 2010. Since then, operating experience was completely satisfactory.

The following two figures are derived from the captured disturbance recordings in this installation. Note that letters B, H and R are used to designate the individual phases in a three-phase system instead of more commonly used L1, L2 and L3 (IEC) or A, B, C (ANSI). Such phase designations are in accordance with the end user practice.

In Figure 3, disturbance recordings captured during direct-on-line starting of the machine with 7,75kV supply (e.g. one half of the rated voltage) is shown. In the three sub-figures the following quantities measured by the protection relay are shown:

a) Three phase-to-ground voltage waveforms at the machine terminals (in primary kV)
b) Three phase current waveforms at 420kV side of the unit transformer (in primary A)
c) Three phase current waveforms at machine neutral point side (in primary kA)

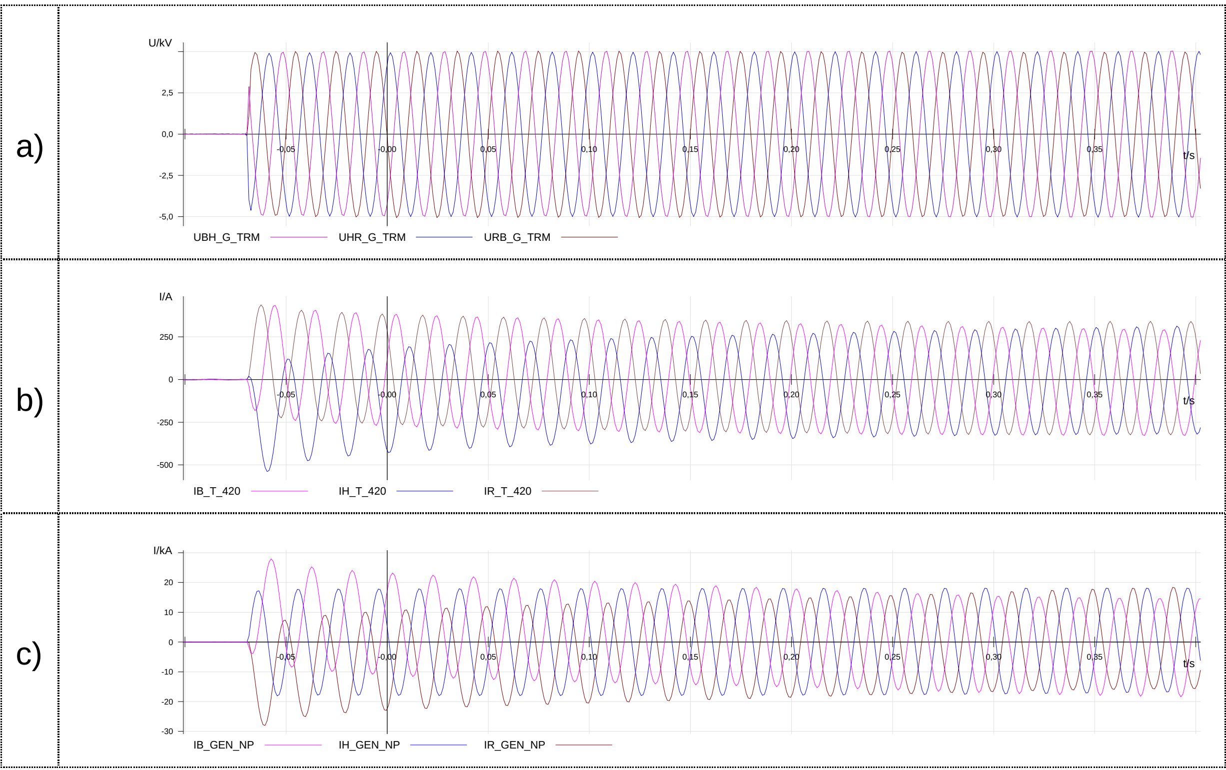
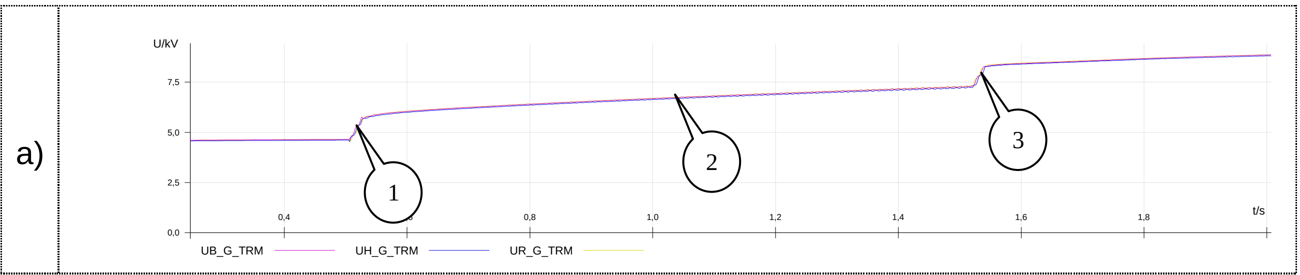


Fig. 3: Direct-on-line starting of the machine with 7,75kV supply (e.g. one half of the rated voltage)

Overall differential protection remained fully stable during this DoL pump starting.

In Figure 4, disturbance recordings captured during switch over of the machine voltage supply from 7,75kV to 15,5kV during pump starting (e.g. from one half of the rated voltage to the rated voltage) is shown. In the three sub-figures the following quantities measured by the protection relay are shown:

a) Three phase-to-ground RMS voltage values at the machine terminals (in primary kV)
b) Three phase current waveforms at 420kV side of the unit transformer (in primary A)
c) Three phase current waveforms at machine neutral point side (in primary kA)



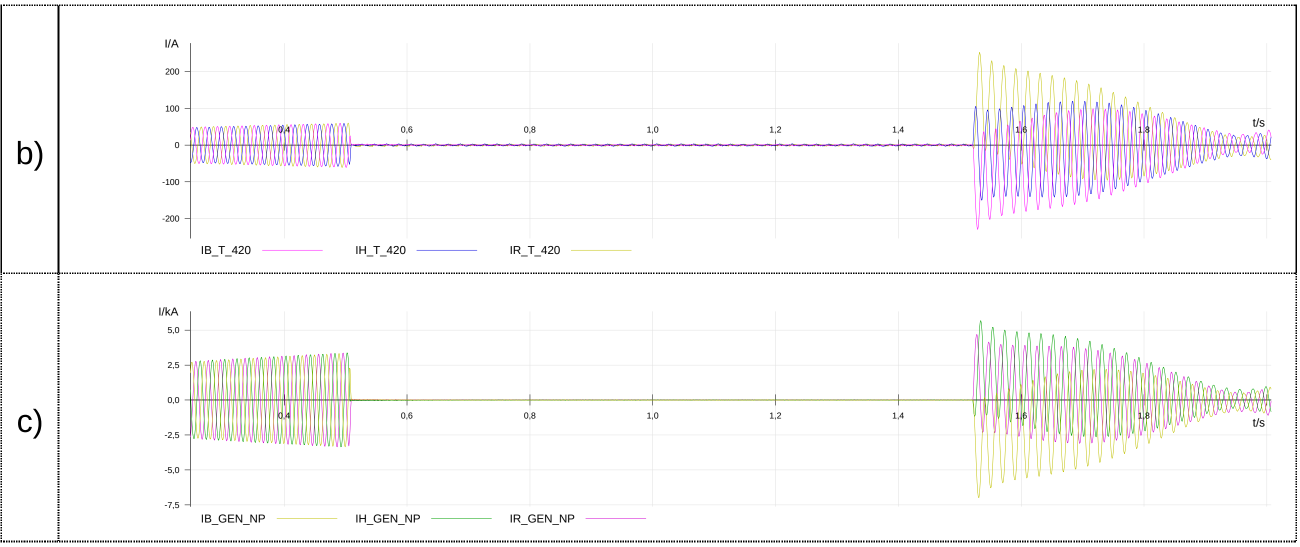


Fig. 4: Switch over of the machine voltage supply from 7,75kV to 15,5kV during pump starting

Please note the following regarding the Figure 4:

- Number 1 in Fig. 4a indicates point in time when CB3 has been opened and the machine becomes effectively disconnected from the HV system. Note that simultaneously current on both sides of the unit transformer disappear.
- Number 2 in Fig. 4a indicates one second long period of time where by increasing the field current, the machine terminal voltage is raised from 50% to approximately 100% of the rated voltage. Note that during this time machine rotational speed is slightly decreased.
- Number 3 in Fig. 4a indicates point in time when CB2 has been closed and machine is re-synchronized with the HV system. Note that currents on both sides of the unit transformer reappear at that instant of time.

During this 1s period for field current forcing, CT current connections towards the overall differential relay have been automatically switched from connections shown in Table 2/row-four to connections shown in Table 2/row-three. As seen from Fig. 4 overall differential relay was fully stable during this pump start.

5 CONCLUSION

Design of the overall differential protection for pump storage power station with relatively complicated primary system setup has been shown. This solution has been implemented by using modern numerical generator protection relay which is in successful operation for almost a year.

For similar applications the following tasks shall be performed in order to properly design differential protection scheme:

- Determine rating plate data for power transformer.
- Find out power transformer bushing markings and how individual CT currents are correlated to them. For pump storage station that would typically require three-line connection diagram for the power station including the machine and unit transformer bushing markings.
- Ensure that on all power transformer sides and under all operating modes currents to the differential protection relay are connected in the same sequence as the relevant bushing markings.
- Only then use the power transformer rating plate data to balance differential protection in accordance with manufacturer recommendations.

Note that the above statements are relevant for all transformer differential relays regardless of their type and manufacturer.

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