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 hydro power plant has at least three different operating modes of the synchronous machine which can cause possible challenges during the design of the plant 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 disconnect switches. These disconnect switches 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 disconnect switches can be crucial for proper design of some protection functions (e.g. overall differential protection 87O) for the generator/motor-transformer unit. For this particular installation, phase reversal disconnect switches 89G and 89P are located in-between the low-voltage bushings of the unit transformer and the synchronous machine (see Figure 1 for more details), thus within the protection zones of the overall differential relay 87O.

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 Figure 2).

The overall differential protection 87O 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 the standard transformer differential protection 87T. 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 Figure 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. from synchronous 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 secondary currents in the relay software.

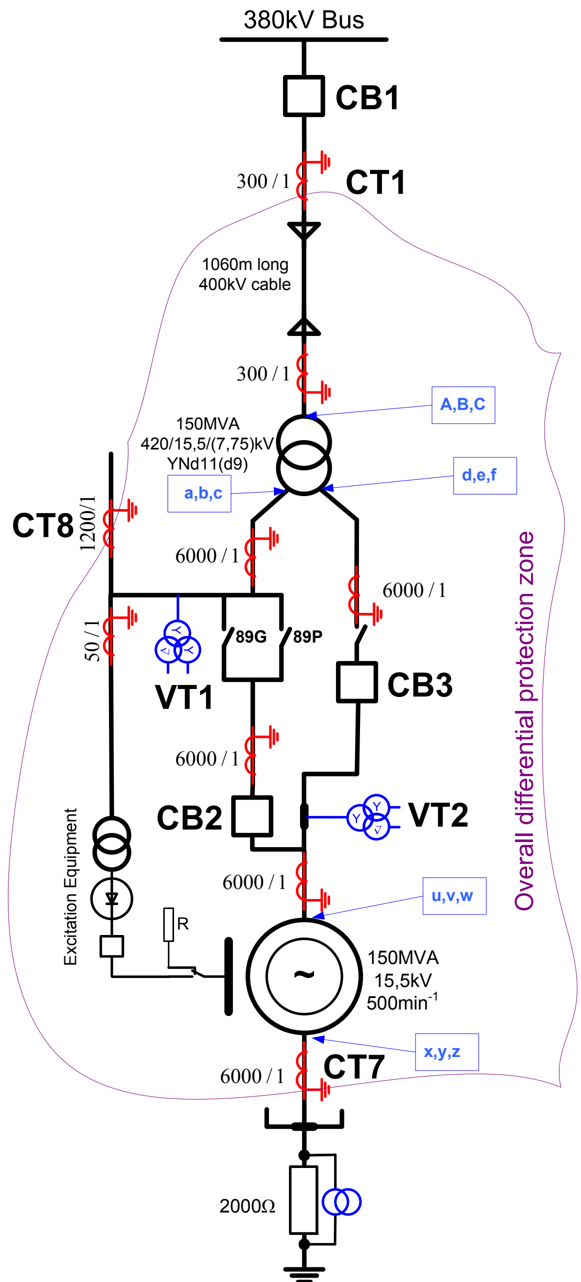

Figure 1: Power plant single line diagram and bushing designations for synchronous machine and unit transformer

2 POWER STATION SETUP

Figure 1 gives overview of one generator/motor-transformer unit, associated current and voltage instrument transformers with their respective ratios and bushing designations for the synchronous machine and the unit transformer. Location of the phase-reversal disconnect switches is also shown. This paper will not present the complete protection scheme for this pump storage hydro power plant because such type of information can be found in reference [3], but it will instead describe the challenges faced during the design of the overall differential protection 87O for this particular power plant.

2.1 Unit transformer design

The unit transformer is actually two-winding transformer with vector group YNd11 (i.e. YD_{AB} per ANSI standard). However, from the middle point of every LV winding (which is connected in delta), three additional bushings marked as “d, e and f” are also made available on the unit transformer, as shown in Figure 2. Such transformer design makes effectively “third phantom winding” with rated voltage 7,75kV and vector group Yd9 (i.e. YD270 per ANSI standard). Note that data for this “third phantom winding” are given in parenthesis in Figure 1 and Figure 2. This “third winding” is only used during synchronous machine starting into pumping mode as described in the next section. Thus, for the overall differential protection 87O this unit transformer shall be handled as a three-winding YNd11d9 power transformer [4].

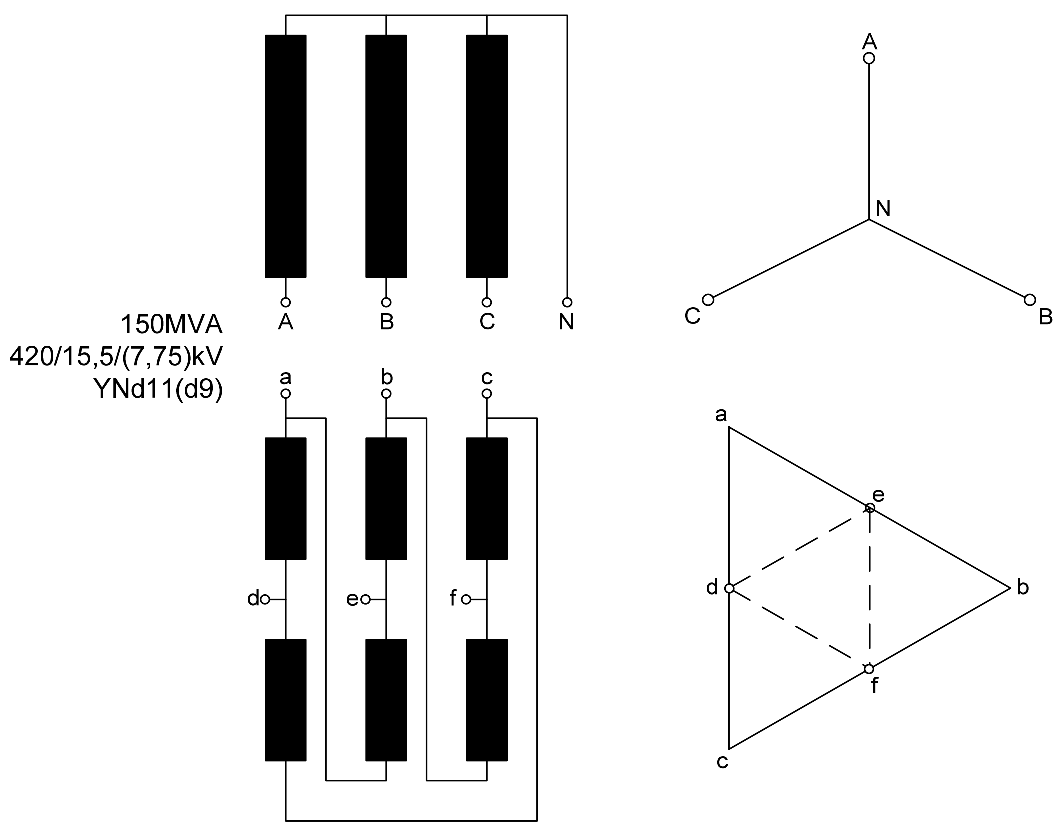

Figure 2: Unit transformer rating plate information with bushing designations

2.2 Machine starting into pumping mode

In every pump storage hydro power plant, synchronous machine starting into pumping mode poses a challenge to the protection scheme designer. Many different solutions are used around the world. In this particular installation, machine 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 and Figure 2. The pump starting sequence contains the following steps:

- Synchronous machine is at standstill
- Unit transformer is energized from the HV system (CB1 is closed, CB2 and CB3 are opened, see Figure 1 for circuit breaker physical locations)
- Phase reversal disconnect switch 89P is closed and switch 89G is open
- By using a compressor water is taken away from the turbine chamber
- Additional starting resistor is inserted in series with the machine rotor winding in order to further reduce the starting current
- Then CB3 is closed and machine is started as an 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 of 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 87O

In any power station application, the overall differential protection 87O 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 Figure 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 out from the protected zone 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. depending on the actual positions of CB2, CB3, 89G and 89P). Possible CT7 connections towards the unit transformer LV bushings are shown in Table 1. Note that bushing designation of the synchronous machine and of the unit transformer is used in this table in order to mark relevant primary connections (see Figure 1 for more details).

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

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

It should be known that any power transformer rating plate data (see Figure 2 for unit transformer rating plate data) are given in respect with its bushing markings [4]. Thus, if the CT secondary currents on all transformer sides are connected to the differential relay in the same order (i.e. sequence) as transformer bushing markings, the transformer rating plate data can be used directly to balance the numerical differential relay. Thus, the following CT connections must be foreseen during engineering and carefully checked during 87O relay commissioning:

- 420kV side phase currents (i.e. L1, L2 & L3) shall be connected to the 87O relay in sequence corresponding the unit transformer HV bushings A, B & C
- 15,5kV side phase currents (i.e. L1, L2 & L3) shall be connected to the 87O relay in sequence corresponding the unit transformer MV bushings a, b & c
- 7,75kV side phase currents (i.e. L1, L2 & L3) shall be connected to the 87O relay in sequence corresponding the unit transformer MV bushings d, e & f

Obviously, in order to follow these rules, the CT7 secondary currents need to be switched in accordance with Table 1 towards the 87O relay.

The used numerical overall differential protection relay [1] is adaptive and it can be engineered to switch in software 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 switching and re-connections of CT7 individual phase 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 via VT2 in the pumping mode of operation. If the VT2 voltage is low (i.e. below 75%) after a pre-set time DoL starting mode is anticipated and appropriate CT7 connections are made in software towards the 87O third winding CT inputs (i.e. 7,75kV side). Once the VT2 voltage increase above 75%, pumping mode of operation is assumed and CT7 currents are re-routed in software towards the 87O second winding CT inputs

(i.e. 15,5kV side). Table 2 summarizes all involved CT connections towards the overall differential protection 87O in this power plant.

Table 2: CT connections to the overall differential protection (see Figure 1)

	87O Winding 1 Currents (i.e. 400kV)	87O Winding 2 Currents (i.e. 15,5kV)	87O Winding 3 Currents (i.e. 7,75kV)
Generating Mode	**CT1:** IA, IB, IC	**CT8:** Ia, Ib, Ic **CT7:** Ix, Iy, Iz*	None
Pumping Mode	**CT1:** IA, IB, IC	**CT8:** Ia, Ib, Ic **CT7:** Iz, Iy, Ix*	None
DoL starting	**CT1:** IA, IB, IC	**CT8:** Ia, Ib, Ic	**CT7:** Iz, Iy, Ix*

* See Table 1 for information

Once these CT connections are arranged the numerical differential relay [1] is balanced by entering the unit transformer rating plate data which are summarized in Table 3. For any other make of 87O relay the same data from this table shall be used to derive appropriate relay settings in accordance with the relay instruction manual.

Because CT7 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.

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

* Two CT inputs from this winding are required for this particular application

Thus, the general rule how to design such complex differential protection scheme is very simple: When from all transformer sides CT secondary currents are connected to the differential relay strictly in accordance (i.e. sequence) which corresponds to the transformer bushing markings, the transformer rated data shall be entered into the relay in order to balance the differential protection.

4 FIELD RECORDINGS

The overall differential protection for the first unit was put in services in June 2010, while the second unit 87O relay is in operation since November 2010. Since then, operating experience of the 87O relays on both units 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 87O 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)

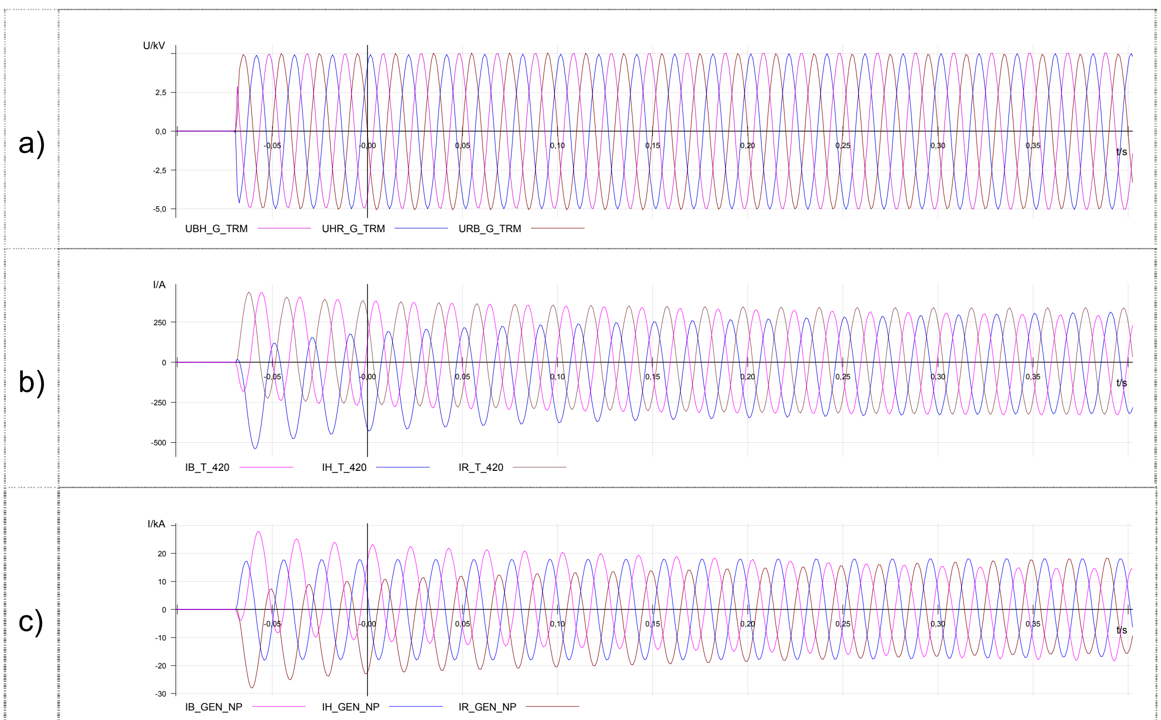

Figure 3: Direct-on-line starting of the machine with 7,75kV supply (e.g. one half of the rated voltage)

Overall differential protection 87O remained fully stable during this DoL 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 full rated voltage) is shown. In the three sub-figures the following quantities measured by the 87O 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)

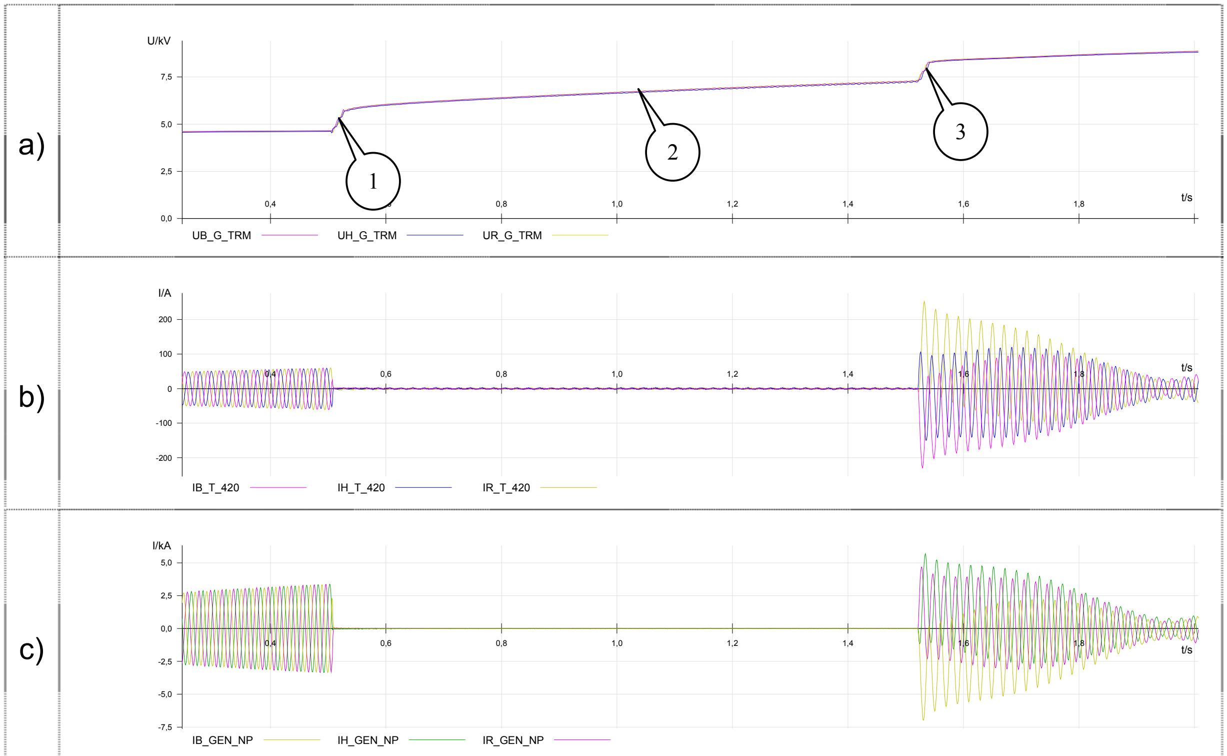

Figure 4 : Switch over of the machine voltage supply from 7,75kV to 15,5kV during pump starting

Please note the following regarding the Figure 4:

- Number 1 in Figure 4a indicates point in time when CB3 has been opened and the machine becomes effectively disconnected from the HV system. Note that at that time instant currents on both sides of the unit transformer disappear.
- Number 2 in Figure 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 Figure 4a indicates point in time when CB2 has been closed and machine is re-synchronized with the HV system at rated voltage. Note that currents on both sides of the unit transformer reappear at that instant of time.

During this 1s period for field current forcing, current connections for CT7 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 Figure 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 more than a year on both units.

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 secondary currents are correlated to them. For pump storage hydro power station that would typically require three-line connection diagram for the power station including the synchronous machine and the unit transformer bushing markings.
- Ensure that on all power transformer sides and under all operating modes of the machine the secondary CT currents towards 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 used relay technology, relay type and manufacturer.

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