Experience with Multi-terminal Line Differential Protection Installed on Series Compensated, 400 kV Line with Five-Ends

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Line differential protection, Charging current compensation.

1. INTRODUCTION

Multi-terminal lines are more often used in modern power systems than before. They are becoming particularly popular in sub-transmission networks (i.e. in networks with rated voltages between 60 kV – 160kV) but also in HV networks. Practical experience with such protection from a commercial installation in Sweden will be presented.

2. INSTALLATION ON SERIES COMPENSATED, 400KV LINE

In Swedish 400 kV national grid Station 2 has been built and existing series compensated 400 kV overhead line previously connected between two stations was converted into line with five-ends, as shown in Figure 1.

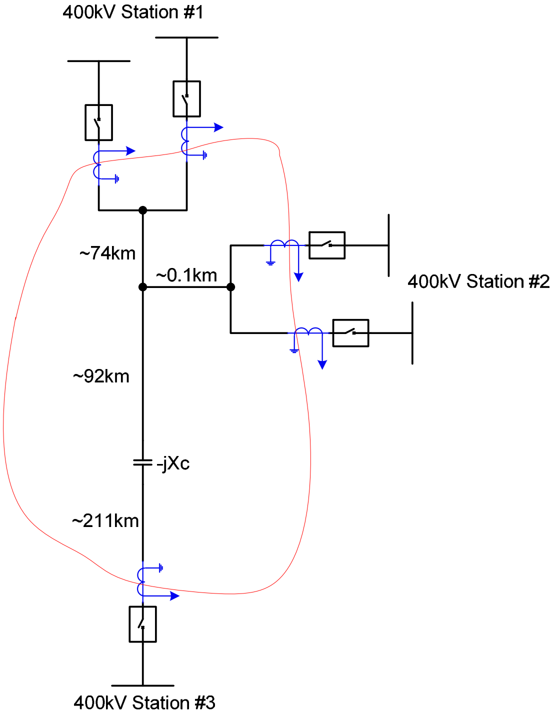

Fig. 1: Five-end, series compensated, 400kV OHL

The following data are valid for this application:

- Positive sequence line impedance $(0.018 + j \cdot 0.275)\ \Omega/km$
- Zero sequence line impedance $(0.26 + j \cdot 0.982)\ \Omega/km$
- Line three-phase reactive power generation 657.5 kVAr/km at 400 kV (circa 350A per phase of charging current at 400 kV over the whole length of the protected line)
- Series capacitor reactance $-j \cdot 73\ \Omega$
- Main CT involved in this scheme have ratio 2000/2 in Station #1, 3000/1 in Station #2 and 2400/2 in Station #3.

For this installation master-master differential protection principle is used (i.e. every differential relay had all five currents available and were able to perform the differential protection algorithm). Distance protection is included in each differential relay in order to provide reserve protection for the line.

The line differential protection scheme uses a telecommunication SDH/PDH network with unspecified route switching. Therefore differential relays utilize the GPS for the time synchronization. In the substations there are 16 × G.703 64 kbit/s channels. The following SDH/PDH configuration is used:

SDH multiplexing (STM-1 or STM-4)à 8 × 2 Mbit/s (E1) à PDH multiplexing à 16 × 64 kbit/s (E0).

3. DESCRIPTION OF THE LINE DIFFERENTIAL FUNCTION

The installed protection is a multi-terminal line differential relay [1] consisting of a traditional unrestrained/restrained differential function in combination with an internal/external fault discriminator. The restrained differential function has a dual biased slope characteristic according to Figure 2. The function is phase segregated except for the case when a power transformer is included in the protected zone. The differential current (Operate current) is the vectorial sum of all measured currents taken separately for each phase and the bias current (Restrain current) is considered as the greatest phase current in any line end and it is common for all three phases.

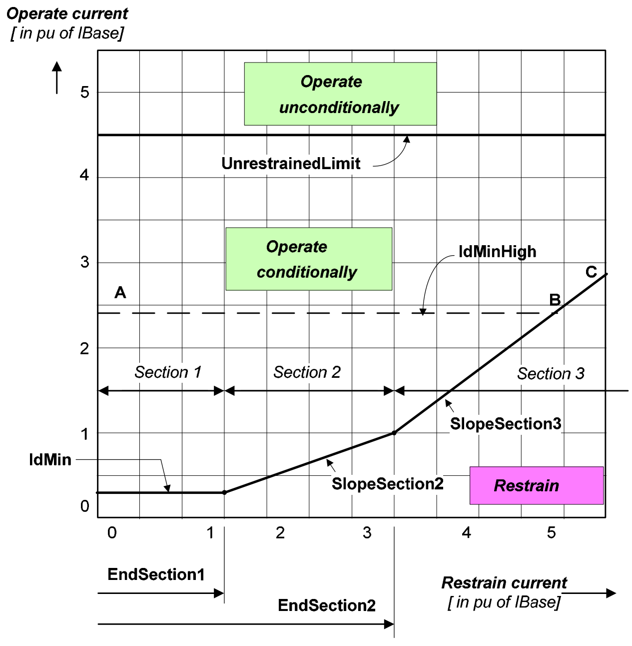

Fig. 2: Line differential protection characteristic

If a fundamental frequency differential current is above the restrain characteristic a start signal is issued for that phase. The instantaneous differential current of the phase is analyzed regarding the 2nd and 5th harmonics. If the function has started and the content of these harmonics are below defined levels the function will trip.

In other case the function will be blocked as long as the harmonics are above the defined levels. The blocking affects the phase where a high level of harmonics has been detected. However with the cross-blocking feature the 2nd and 5th harmonic blocking in one phase will also block the differential function of the other phases. There is also an unrestrained differential function without any stabilization from the 2nd and 5th harmonics.

The fault discriminator distinguishes between internal and external faults and is based on an analysis of the negative sequence current component at the ends of the protected circuit. It works such that the phase angle of the negative sequence current component from the local end is compared with the phase angle of the sum of the negative sequence current components from the remote ends. The characteristic for this fault discriminator is shown in Figure 3, where the directional characteristic is defined by the two setting parameters *IminNegSeq* and *NegSeqROA*.

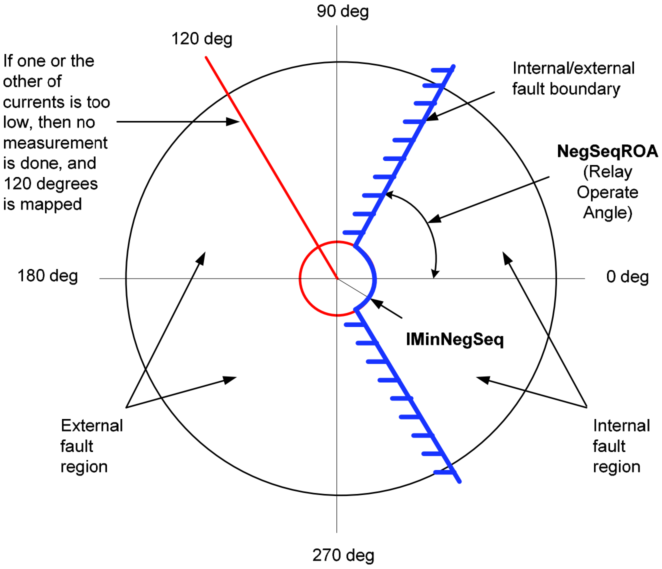

Fig. 3: Operating characteristic of the internal/external fault discriminator

The reference direction of currents is considered to be towards the line. Thus, when both currents to be compared have this direction, the phase difference between them will ideally be close to zero and an internal fault can be suspected. In the opposite case, when one current is entering and the other is leaving the protected object, the phase difference will ideally be 180 degree and an external fault can be expected. In case either the local or the sum of the remote negative sequence currents, or both, is below the set minimum current level, *IminNegSeq*, the fault discriminator will not make any fault classification and the value 120 degree is set. This value is an indication that negative sequence directional comparison has not been possible to do and the classification is neither internal fault nor external fault.

When a fault is classified as internal, a trip is issued under the condition that the dual slope restrained function has started. In most cases the harmonic blocking is overridden. A classification as external fault results in an increase of the restrained characteristic trip values from *IdMin* to *IdMinHigh*.

4. CHARGING CURRENT COMPENSATION

The normal charging currents of overhead lines and cables are capacitive and of the positive-sequence nature. They are related and proportional to the distributed line capacitances between phases, and between each phase conductor and earth. For long high-voltage power lines and particularly HV cables such charging currents may have relatively big magnitude. Such charging current are seen as false differential currents by the line differential protection.

In case of a line with two ends, it is possible to compensate for these currents by measuring voltage at both line ends and assuming a Π-equivalent circuit for the protected line [4]. However for a multi-terminal line such type of compensation would be quite complicated and it would require exact description of the line topology. Here a new approach is proposed which is not dependent on the voltage measurement and it can be used for arbitrary multi-end line configuration. Simply the line differential protection learns the amount of false differential current value over the time and subtracts it from the presently measured fundamental frequency, RMS differential currents. By doing so the sensitivity of the line differential protection is increased for the high resistance internal fault, while the operation of the line differential protection is not much disturbed for all types of external faults and heavy internal faults. Note that only the symmetrical pre-fault charging currents are subtracted from the fundamental frequency differential currents in a phase-wise manner.

The simplified algorithm description can be summarized as follows. As long as no disturbance has been detected, false fundamental frequency differential current magnitudes are stored over a period of last five cycles in relay internal memory. Then the average value over the oldest three stored cycles is calculated and used as charging current magnitude. Value of this charging current magnitude is not updated under faults, or under disturbed operating conditions. The updating process is resumed five cycles after normal through-load conditions have been restored and at the beginning it will be done in couple of steps. Main principles of this algorithm are shown in Figure 4. The estimated value of the charging current is available in primary amperes as a service values from the multi-terminal differential protection function [1].

By continuously applying such charging current compensation method the RMS value of the fundamental frequency differential currents in all three phases will practically be zero or very close to zero during normal through-load condition. Thus the calculated fundamental frequency differential currents during the fault condition will not be affected by the line charging current. Note that this is an approximate method. However it is a very efficient way to increase the sensitivity of the line differential protection for high resistive internal faults which is the prime task of the charging current compensation algorithm. As shown in this paper such approach even works for long, series compensated overhead lines.

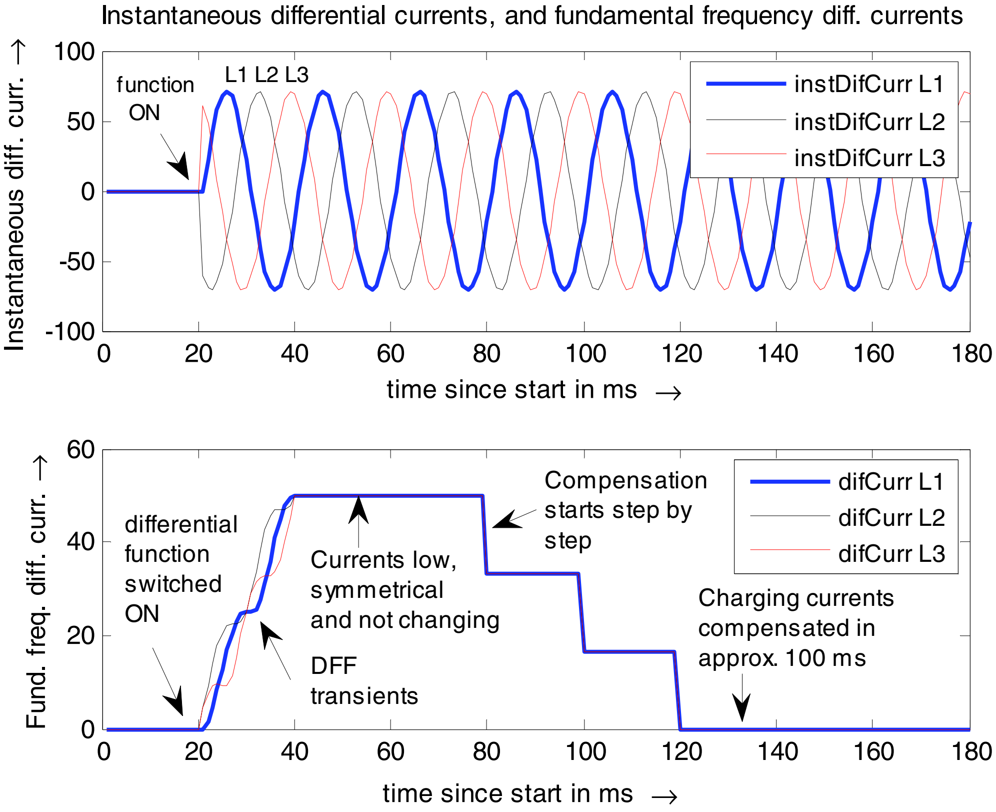

Fig. 4: Charging current compensation algorithm operating principles

5. ACTUAL INTERNAL FAULTS CAPTURED IN THIS INSTALLATION

The multiterminal line differential protection has been in service on this line for more than 18 months. Both external and internal faults have happened and protection has behaved correctly. Two captured recordings in this installation will be presented here. Both recordings were captured by line differential protection IED installed in Station #3. The first recording is an internal L2-L3-Gnd fault which was caused by lightning. The fault location was estimated to be 99 km from Station #1 and estimated fault resistance was around 24 Ohms primary. The second recording is an internal L2-Gnd fault. The fault location was estimated to be 7km from Station #1 and the fault resistance was estimated to be around 8 Ohms primary. The cause of this fault is unknown. Differential protection has operated properly for both internal faults.

In the next two figures the following traces captured by the line differential protection IED installed in Station #3 are shown:

a) Phase to ground voltage waveforms in Station #3 in kV

b) Three-phase current waveforms in Station #3 in kA

c) Bias current RMS value, three-phase differential current RMS values and negative sequence differential current RMS value in kA as calculated by the line differential protection relay

d) Three-phase differential current waveforms in primary amperes as calculated by the line differential protection relay.

Note that on all traces differential protection trip instant is shown as vertical line at t = 0,000 s (i.e. triggering signal for the disturbance).

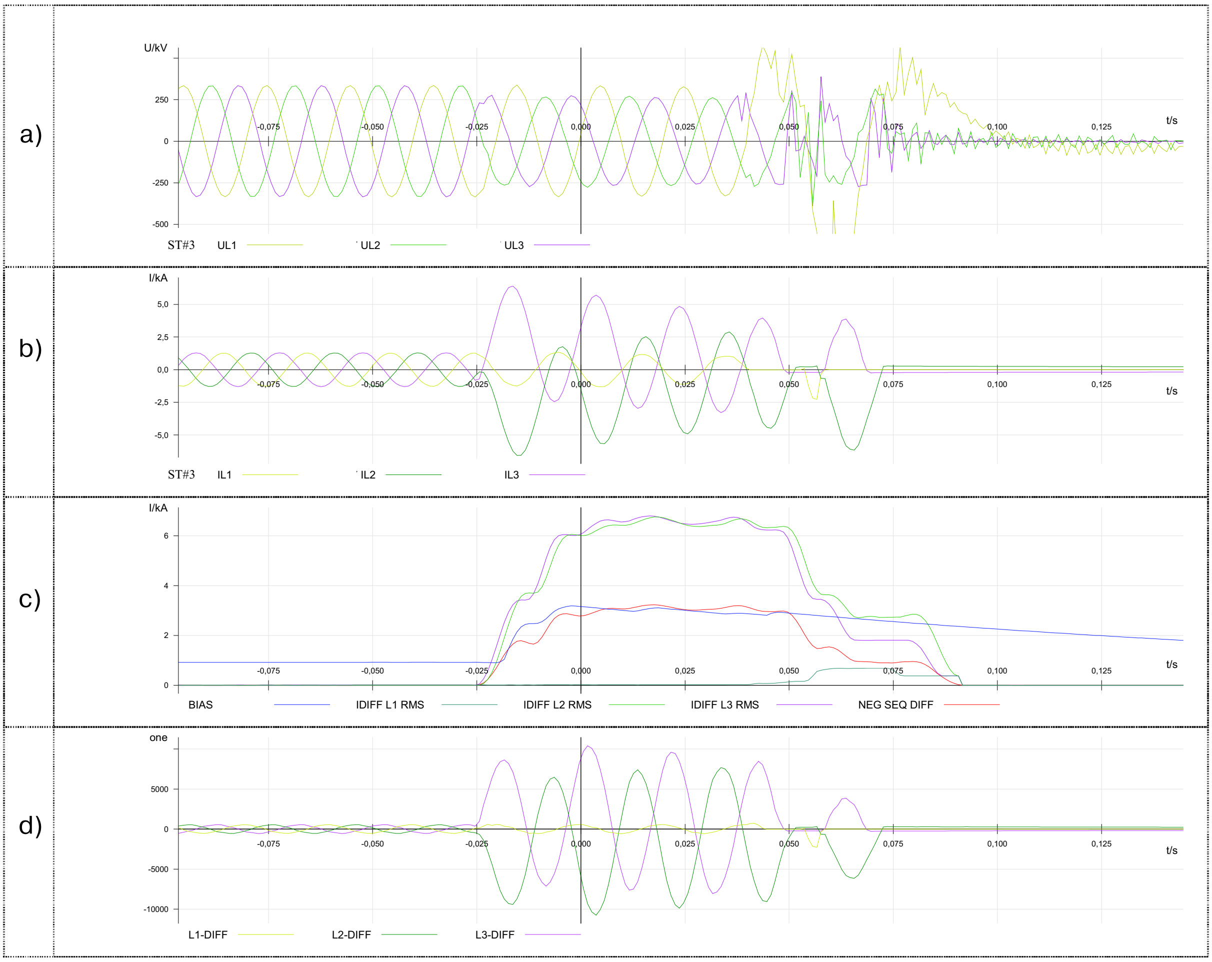

Fig. 5: Internal L2-L3-Gnd fault located 99km from Station #1

From Figure 5 it is obvious that the fault is L2-L3-Gnd but that its location is remote from Station #3. It is interesting to notice that instantaneous differential currents are present before the fault with equivalent magnitude of approximately 380A in all three phases as shown in Figure 5d, while the RMS differential currents are practically zero, as shown in Figure 5c, due to charging current compensation method previously described. Note that the RMS differential current for non-faulty phase remains zero during the fault. The voltage RMS value before the fault was 410 kV at Station #3.

From Figure 6 it is obvious that the fault is L2-Gnd but that its location is remote from Station #3. It is interesting to notice that instantaneous differential currents are present before the fault with equivalent magnitude of approximately 380A in all three phases as shown in Figure 6d, while the RMS differential currents are practically zero, as shown in Figure 6c, due to charging current compensation method previously described. Note that the RMS differential currents for non-faulty phases remain zero during the fault. The voltage RMS value before the fault was 409 kV at Station #3.

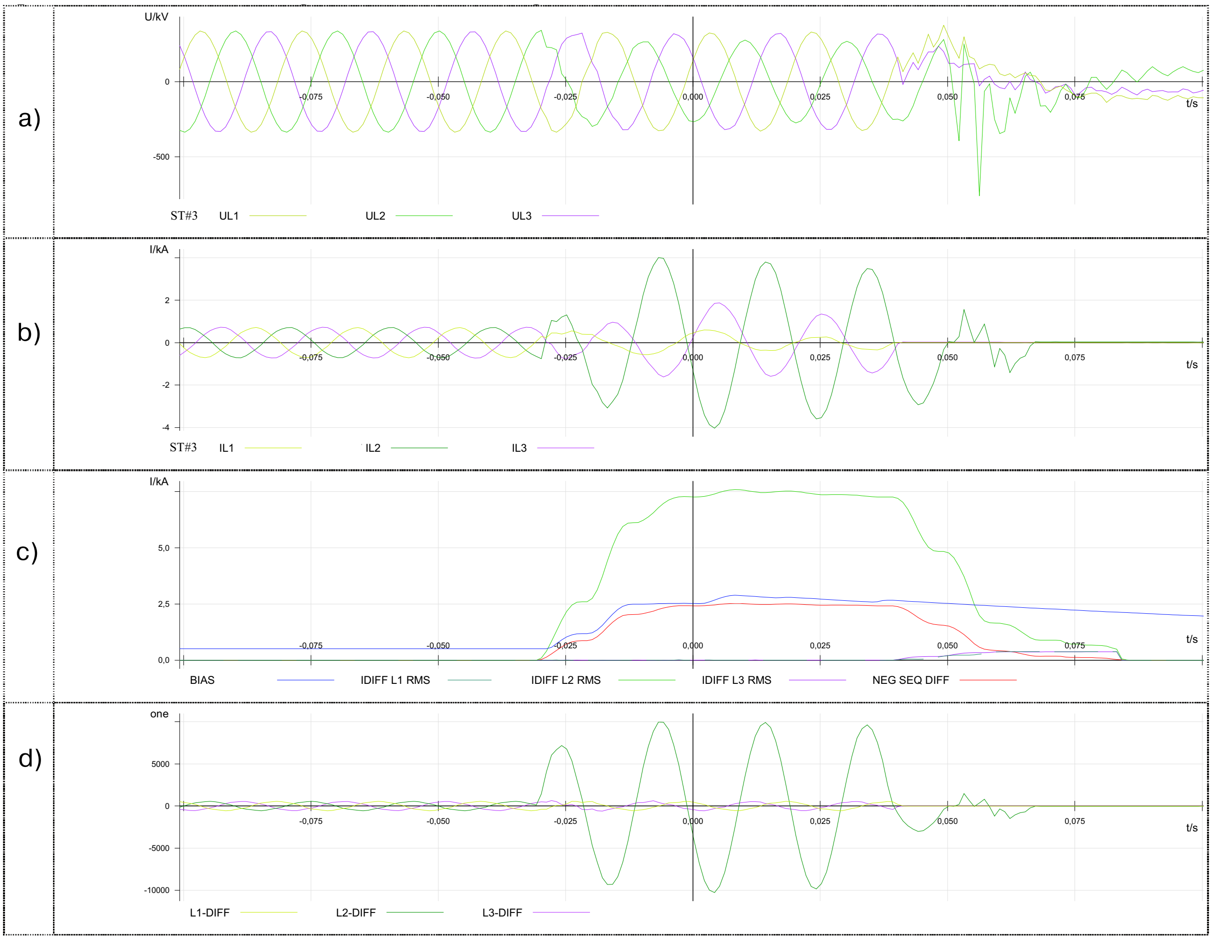

Fig. 6: Internal L2-Gnd fault located 7km from Station #1

6. CONCLUSION

In this paper it has been shown that the multi-terminal line differential protection is a good solution for protection of long series compensated, high-voltage lines with more than two ends. The proposed charging current compensation method, independent from voltage measurements, seems to work very well for such long overhead line configurations. Combination of multi-terminal line differential protection and distance protection provides good protection solution for such lines.

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