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Problems and Solutions for AC Transmission Line Protection under Extreme Conditions caused by Very Long HVDC Cables

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Summary

NorNed is an HVDC link that will connect the 300 kV transmission system in Norway and the 400 kV transmission system in the Netherlands. The transmission capacity will be 700 MW and the voltage ±450 kV. The 580 km HVDC cable will be the longest submarine cable in the world. The link is scheduled to be commissioned at the end of 2007.

If commutation failures occur in the HVDC converter due to AC power system faults the DC cable capacitance will discharge. The DC cable discharge current will in some instances be injected into the faulty AC power system. As the NorNed cable is very long the discharge current will be of considerable magnitude and will expose the AC protection systems to extreme conditions.

Existing distance relays in the Norwegian power system were tested by Statnett by injection of calculated secondary fault voltages and currents including cable discharge currents. The result was that there is a considerable risk of unwanted operations for some distance relays in case of commutation failures in the HVDC link. It was concluded that distance protection relays are not suitable to use for some of the transmission lines and should be replaced by protection based on another principle.

It was decided to carry out comprehensive tests of a newly developed line differential relay to verify its ability to operate in these difficult applications. The main problem for the protection systems is saturation of the CTs caused by the DC discharge current. As the remanence of the closed core CTs is of major importance for the performance of the protection the tests were carried out with several combinations of remanence including extremely high levels of remanence such as 75 and 85 %.

The tests have verified that the tested line differential protection has the capability to operate correctly in power systems close to HVDC links with very long DC cables. The protection performed excellent and was stable for all relevant external fault cases. All internal faults were tripped and the average operate time was 24 ms. Minimum operate time was 20 ms and maximum 38 ms. The few operations with operate time > 30 ms occurred for cases with low fault currents and with 85 % remanence. Considering the difficult fault cases the average operate time of 24 ms is very good.

Keywords

Line differential protection, HVDC, DC cable discharge current, CT saturation, remanence

1 Background

NorNed is an HVDC link that will connect the 300 kV transmission system in Norway and the 400 kV transmission system in the Netherlands. The transmission capacity will be 700 MW and the voltage ±450 kV. The 580 km HVDC cable will be the longest submarine cable in the world. The link is scheduled to be commissioned at the end of 2007.

In case of AC power system faults like phase-to-phase short circuits and phase-to-earth faults there is a risk that commutation failures will occur in the HVDC converter. This will result in discharge of the

DC cable capacitance and the discharge current will in some instances be injected into the AC power system through the valve bridge and the converter transformers. As the NorNed cable is very long the discharge current will be of considerable magnitude. The DC discharge current will be superposed on the AC fault current. The resulting shape and magnitude can vary much depending on many different factors but the DC discharge pulses will often cause total fault currents without any zero crossings during approximately 50 ms. Figure 1 shows an example of such a current.

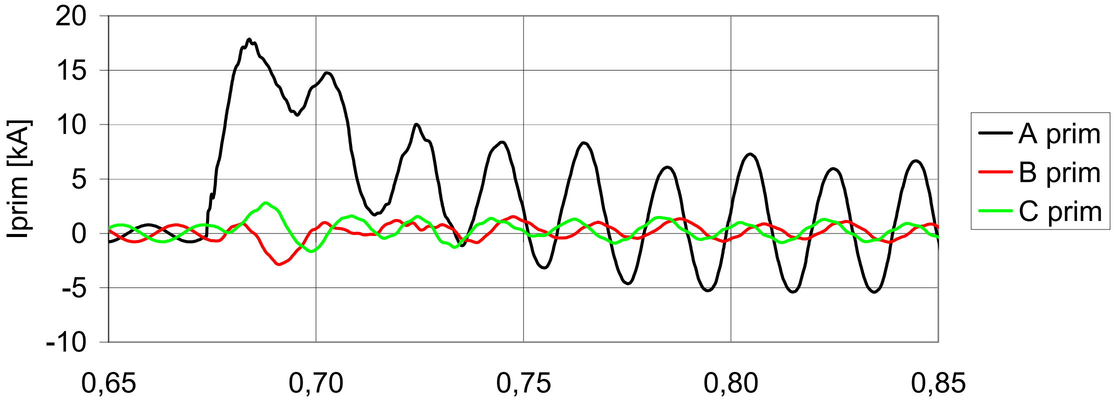

Figure 1. Primary phase to earth fault current including the DC discharge current

2 Problems and possible solutions for the protection

Protection relays intended for use in AC power systems are designed mainly for AC fault currents including all degree of DC offset. The CT requirements are specified for the same conditions often also considering a certain level of remanence. Fault currents with DC discharge currents will expose the protection systems to extreme conditions. The main problem for the protection systems is saturation of the CTs. Figure 2 shows the resulting secondary current if the current above (Figure 1) is transformed through a 60 VA CT class 5P15 with 70 % remanence.

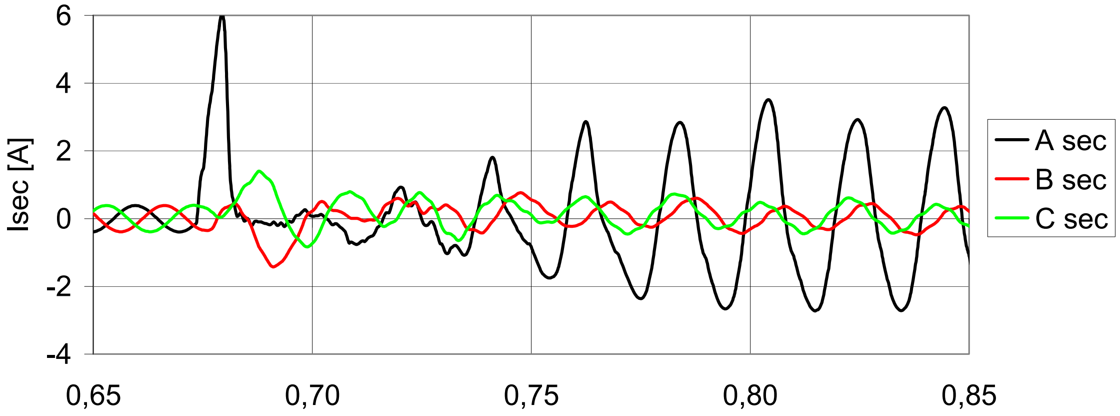

Figure 2. Secondary phase to earth fault current from a 60 VA CT class 5P15 with 70 % remanence

In case the CTs should be overdimensioned to such a degree that saturation is avoided and the primary current is transformed correctly to the secondary side there is a considerable risk that the relay input transformers will saturate and the protection algorithms anyhow must operate under very difficult conditions with distorted signals. There is a real risk that the protection will operate with unacceptable additional time delays for faults within the protected zone or even worse that it will give unwanted operations for faults outside the protected zone.

Statnett tested existing distance relays in the Norwegian power system by injection of calculated secondary fault voltages and currents including cable discharge currents. The result was that there is a considerable risk of unwanted operations for some distance relays in case of commutation failures in the HVDC link. It is not acceptable if several AC transmission lines will trip incorrectly simultaneously as the HVDC link is temporary blocked due to the commutation failure. The conclusion was that distance protection relays are not suitable to use for some of the transmission lines and should be replaced by protection based on another principle.

Line differential protection seemed to be the protection principle that should have the best possibilities to operate correctly for these difficult fault cases. However, as the fault currents are more extreme than the currents normally used for verification of the performance of the protection relays it was decided to carry out comprehensive tests to verify correct operation of the protection. Both security and dependability of the protection had to be verified.

3 Description of the line differential function

The tested protection was a newly developed multi-terminal line differential relay 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 3. 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 is common for all three phases.

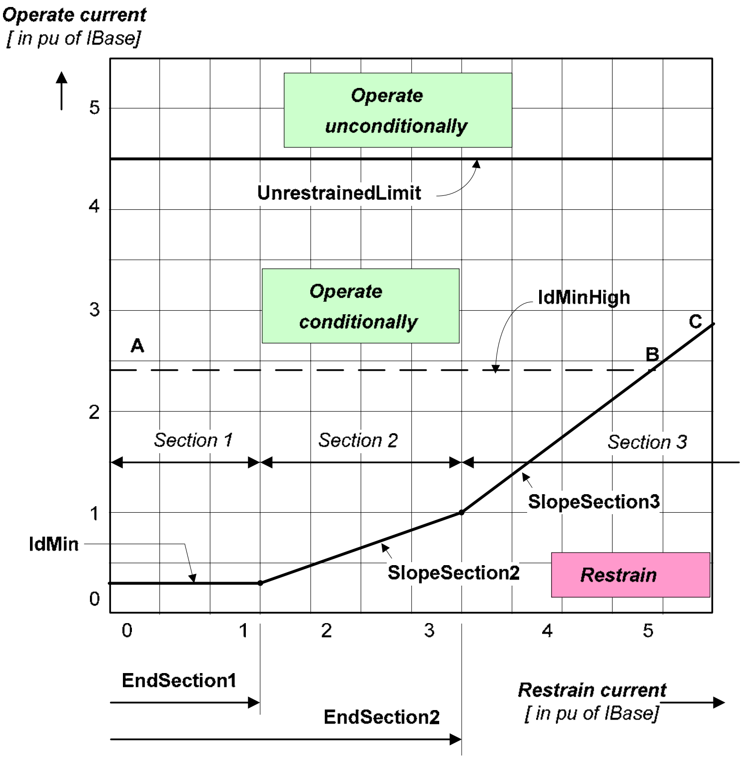

Figure 3. Line differential protection characteristic

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 at the ends of the protected circuit. It works such that the phase angle of the negative sequence current from the local end is compared with the phase angle of the sum of the negative sequence currents from the remote ends. The characteristic for this fault discriminator is shown in Figure 4, where the directional characteristic is defined by the two setting parameters IminNegSeq and NegSeqROA.

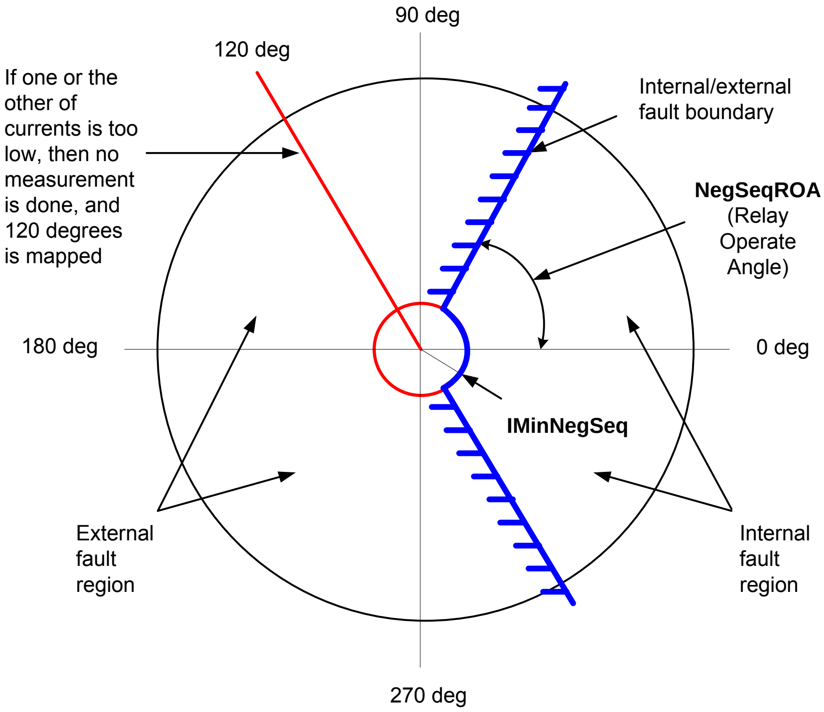

Figure 4. Operating characteristic of the internal/external fault discriminator

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 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 Test methods and test cases

The fault currents were calculated based on a PSCAD model of the real Statnett 300 kV transmission system including both Skagerrak and NorNed HVDC links. The results were saved in Comtrade files that were used in different ways for testing the protection. Statnett wanted to be able to test in-house with portable test equipment. For this purpose it was necessary to include models of CTs in the PSCAD model and calculate the secondary fault currents.

Current transformers with closed iron core are the most common types of CTs and also used in the Statnett transmission system. In this type of CT a remanent flux will remain after interruption of the primary current. Once remanence is established in the CT it will remain in the core until the CT is demagnetized. Normal load conditions will not have any significant influence on the remanence level. If the CT is exposed for high currents the remanence level will be changed. In practice the remanence can vary from 0-80% of the maximum flux according to studies carried out on CTs that had been in service in power systems. The probability of remanence of 75 % or higher must be considered as very low. Depending on the direction of the fault current the remanence can decrease or increase the available margin for flux and consequently both reduce and prolong the time to saturation.

External faults are the most critical fault cases for differential protection. The protection must not give any unwanted operations in these cases. If CTs in both ends saturate at the same time the resulting differential current will be small and not cause any major problem. However, if the CT in one end saturates but not in the other end or if they just saturate at different time it will create potential difficulties for the protection.

When calculating the secondary currents CT data and the combination of remanence levels in the line ends and phases must be specified. As the possible combinations are numerous and the calculations were time consuming the numbers of calculation had to be limited. The test cases were based on the real Statnett 300 kV transmission system. One medium and one maximum SCC model was used. All together 26 external and 25 internal fault cases comprising phase to earth and phase to phase to earth faults were specified and calculated. Combinations of 0, 40 and 75 % remanence were included.

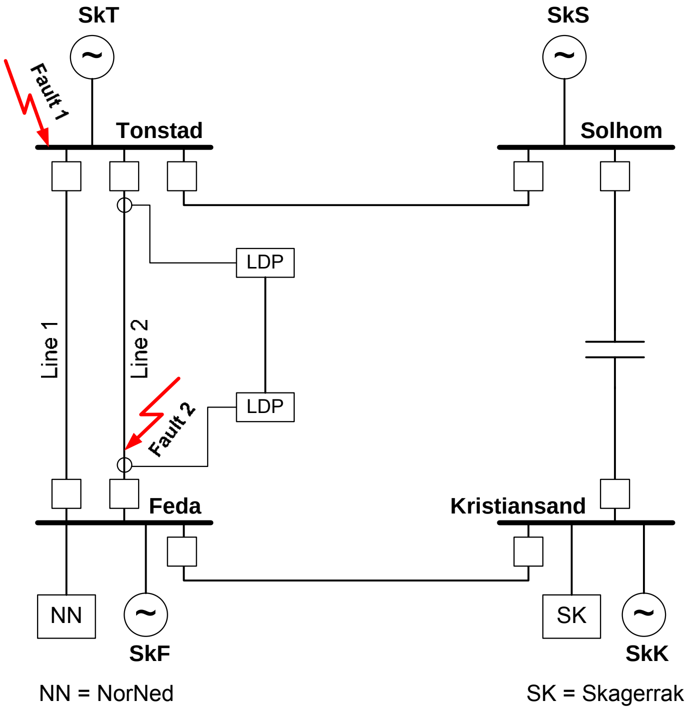

Figure 5. Basic power system for the test cases

To be able to perform more comprehensive tests including more combinations of remanence primary fault currents were calculated for a simplified network model of the Statnett 300 kV system around NorNed and Skagerrak HVDC converter stations (Figure 5). Ten different test cases were defined based on this system to be able to test different combinations and cases e.g. strong or weak power systems. The values of the short circuit source impedances were changed and lines were taken out of operation. Two of the cases were future extremely difficult cases including a NorNed link duplicated with a second HVDC cable. Phase to earth, phase to phase, phase to phase to earth and three-phase faults were calculated for one internal and one external fault position for all ten cases. The results were saved in Comtrade files and imported to a RTDS simulator and run through CT models in the RTDS. The line differential protection was tested by injecting the secondary output currents from the RTDS amplifiers to the relay. A large number of test cases were run with different sizes of the CTs and with different combinations of remanence.

5 Test results

At the initial tests all ten fault cases were run with all fault types for internal and external faults. The combinations of remanence were limited with 75 % as maximum. The tests were performed both with strong CTs in both line ends and with weak CTs in the line ends. A few unwanted operations were observed. Some of the most difficult fault cases were repeatedly retested with high remanence in different directions in combinations with strong CTs in one line end and weak CTs in the other end. These initial tests gave valuable knowledge how to optimize the settings to be able to avoid unwanted operations.

The tests also gave information about which of the power system fault cases that were most difficult. Based on this just the five most difficult cases were used in the final testing. Moreover the station Feda was equipped with weak CTs and station Tonstad with strong CTs. In addition more combinations of high remanence cases were tested. For the final testing the following combinations of remanence were used:

Fault types	**Remanence [%]**					
	$CTL1_{Feda}$	$CTL2_{Feda}$	$CTL3_{Feda}$	$CTL1_{Tonstad}$	$CTL2_{Tonstad}$	$CTL3_{Tonstad}$
L1N (Internal and external faults)	0	0	0	0	0	0
	50	50	50	0	0	0
	75	75	75	-75	-75	-75
	75	75	75	75	75	75
	85	85	85	-85	-85	-85
	85	85	85	85	85	85
L1L2 L1L2N (Internal and external faults)	0	0	0	0	0	0
	50	50	50	0	0	0
	50	-50	50	0	0	0
	75	75	75	-75	-75	-75
	75	75	75	75	75	75
	75	-75	75	-75	75	-75
	75	-75	75	75	-75	75
	85	85	85	-85	-85	-85
	85	85	85	85	85	85
	85	-85	85	-85	85	-85
	85	-85	85	85	-85	85
L1L2L3N (Internal and external faults)	0	0	0	0	0	0
	50	50	50	0	0	0
	75	75	75	0	0	0
	75	75	75	-75	-75	-75
	75	75	75	75	75	75
	85	85	85	-85	-85	-85
	85	85	85	85	85	85

Example of primary and secondary currents from station Feda and measured differential current for an external fault is shown below in Figure 6. The protection performed correct and did not operate though a sensitivity setting of 30 % (0,30 A).

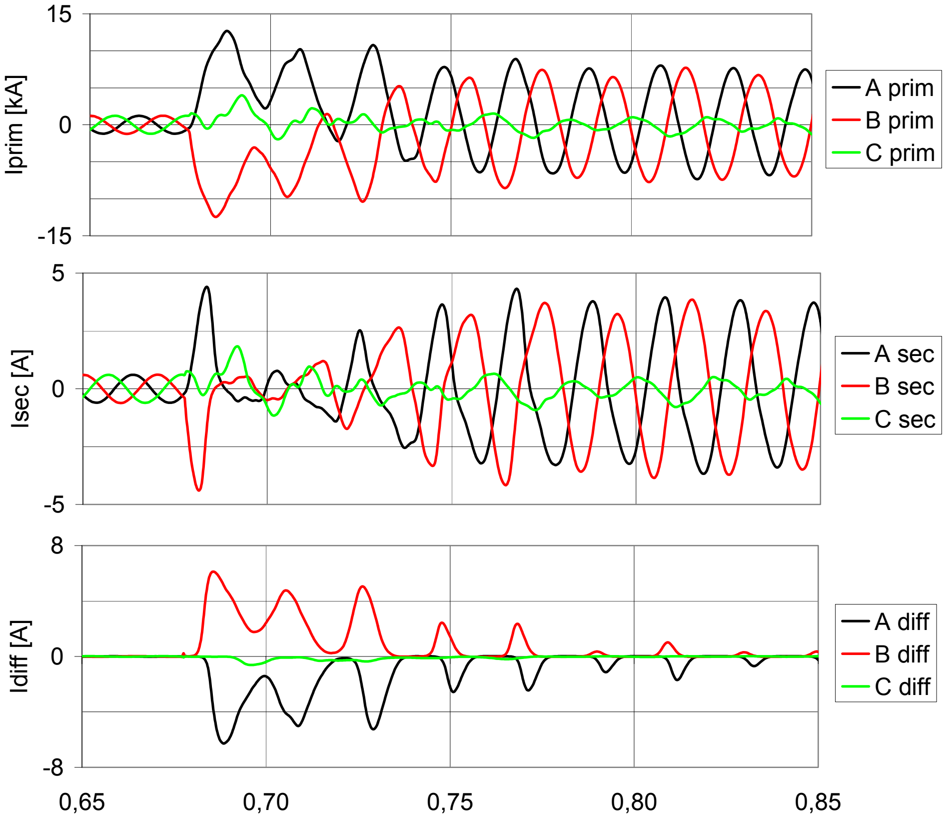

Figure 6. External phase to phase to earth fault. Primary and secondary currents in Feda and the resulting differential current. The remanence in some CTs was 85 %

Each test series comprised 350 intentionally difficult shots, 175 internal and 175 external faults. It was repeated three times, all together 525 internal and 525 external shots. There were all together 6 unwanted operations and all were three-phase faults in the future case with NorNed link duplicated with a second HVDC cable and with 75 % remanence. Further fine-tuning of some setting should probably prevent also these operations.

For the internal faults the average operate time was 24 ms, minimum 20 ms and maximum 38 ms. The operate time was > 30 ms for 14 faults. All of them were in cases with low fault currents and with 85 % remanence.

6 Conclusions

Comprehensive tests have verified that a newly developed line differential protection has the capability to operate correctly in power systems close to HVDC links with very long DC cables. In these applications the protection systems can be exposed to extreme conditions in case of commutation failures causing high DC discharge currents superposed on the AC fault current.

The test cases were based on a PSCAD model of the real Statnett 300 kV transmission system including both the Skagerrak and the NorNed HVDC links. Future cases with two NorNed links in parallel were also included. The main problem for the protection systems is saturation of the CTs caused of the DC discharge current. As the remanence of the closed core CTs is of major importance for the performance and problems of the protection the tests were carried out with several combinations of remanence including extremely high levels of remanence such as 75 and 85 %. Normally these levels of remanence are considered unlikely to happen.

After initial tests it was possible to find suitable settings that were used for all fault cases. The line differential protection performed excellent and was stable for all relevant external fault cases. A few exceptional unwanted operations happened but in view of the extremely difficult fault cases this was acceptable and of minor importance.

All internal faults were tripped and the average operate time was 24 ms. Minimum operate time was 20 ms and maximum 38 ms. All operate time > 30 ms occurred in cases with low fault currents and with 85 % remanence. Considering the difficult fault cases the average operate time of 24 ms is very good.

It was also concluded that the relay manufacturers' guidelines regarding requirements for dimensioning of CTs are based on normal conditions in AC power systems and do not consider such extreme cases as DC discharge currents from HVDC cables. Therefore, dimensioning of the CTs should be based on additional studies in these cases.

The standard setting recommendations from the relay manufacturers are based on conditions in normal AC power systems but it should be possible to use the final settings of the protection identified during these tests as default settings in similar applications. However, it is of course always of great value if the settings for these kinds of extreme conditions are possible to verify by suitable simulations and tests.