System Protection Schemes

Appendix 9 to SOA Annex OS

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1 Background

Automatic *system protection* is used to limit the impact of faults by means of measures beyond disconnecting the defective component. *System protection* can be used to increase *system security*, *transmission capacity*, or a combination of these.

Automatic system protection uses two different principles of operation. One of these is system protection that is activated via measurements of the system state, e.g. the voltage at a critical point or the system frequency. The other is system protection that is activated by predetermined events, e.g. one or more relay signals from the facilities' protective equipment.

Automatic system protection limits the consequences of operational disturbances in one or more of the following ways:

- quick changes in flows on DC facilities, *emergency power*
- production shedding (PFK) or downward regulation of production
- automatic *load shedding* (AFK) and, in some cases, reactive shunts
- start-up of production
- network switching

This appendix describes the automated system protection schemes used in the Nordic power system. Manual operations to handle overload and temporary increased system security are not covered in this appendix.

2 General requirement to system protection schemes

For *system protection* the following requirements have been set:

- An analysis must be done which shows the consequences for the power system in the event of a correct, unwarranted, and missing function considering simultaneously the other system protections.
- In the event of a correct or unwarranted function, *serious operational disturbances* will not be accepted in other *subsystems*.
- If the above consequence analysis shows that a missing function can entail *serious operational disturbances* for other *subsystems*, the following technical requirements shall apply to the *system protection* function:
  - Redundant telecommunications shall exist in cases where system protection is dependent on telecommunications. This means that communications between the stations concerned shall be entirely duplicated. If the auxiliary power feed for one of the communications systems fails, then the other must not be affected. In practice, this means that batteries, telecom terminals, converters and communication paths must be duplicated. Communication paths may not, on any section, share connections, leads, opto cables or similar. They must take geographically separated routes. Multiplexed links can be used but communications shall use separated multiplexes that are not fed by the same battery. Having separate fuses on the same battery, does not constitute full redundancy.
  - There must be real time monitoring of telecommunications.
  - There must be a redundant and independent "triggering function". If this relates to breakers, it means that the breaker has two trip magnets. Breaker fault protection shall be used to safeguard breaker operation if the ordinary breakers are not functioning correctly

- The control facility and telecommunications standard shall be on the same acceptable reliability level as the one applicable to primary relay protection

- If a consequence analysis shows that a missing function will not entail *serious operational disturbances* for other *subsystems*, the relevant *subsystem's system operator* will decide which requirements apply to the *system protection* function.
- *If a consequence analysis shows that a correct, unwarranted or missing function can lead to more extensive consequences than dimensioning faults, system protection must be accepted* separately between the parties.

3 System protection activated by frequency deviations

A low frequency during *operational disturbances* is traditionally dealt with using *frequency-controlled disturbance reserve* (FCR)

Frequency controlled disturbance reserve is dimensioned to maintain the frequency within permissible limits in the event of *operational disturbances*. If this is not successful and the frequency continues to drop, *load shedding* might curb the frequency drop. The use of frequency-controlled changes in flows on HVDC installations, *emergency power*, is to prevent major frequency drops.

A high frequency is traditionally dealt with using the downward regulation of production or, in extreme situations, using *production shedding*. In this case too, use of the frequency-controlled changes in flows on HVDC installations is implemented to prevent major frequency increase.

3.1 Emergency Power Control (EPC) from HVDC interconnections

Emergency power is power control on HVDC links activated by automatic systems on both sides of the respective HVDC link.

At the DC facilities, system protection is constituted by emergency power settings at the converter stations. Activation criteria can be locally measured frequency and voltage or via telecoms based on the supplied signal. In the event of activation, any ongoing normal regulation will be interrupted. Activation over and above the agreed limits and regulation back to plan may not occur until the counterparty has approved this.

The maximum impact on flows of different HVDC interconnections during frequency deviations in the Nordic area can be seen in table 1. It should be pointed out, however, that if a HVDC installation is performing a full import to an area with a low frequency, it will not be able to contribute to *emergency power*.

SOC decided in their 62nd meeting 30 September 2020 that the proposed Mutual Frequency Support framework was applicable to current operational HVDC links (where technically possible) and all future HVDC links. TSOs that have an HVDC interconnector shall initiate the implementation with the objective of completing the technical adaptations within a period of no longer than 5 years. According to this the Requirements for LFSM on HVDC must be implemented by January 1st, 2026. This might have an impact on the existing EPC as described in table 1.

Table 1: Frequency controlled emergency power

Bipol	f(Hz)	dP (MW)	Delay (ms)
Skagerak 1-2	49,0	120	60
Skagerak 3-4	49,0	120	60
NordBalt	49,1	300	500
SwePol	49,1	300	500
Baltic Cable	49,2	300	500
Skagerak 1-2	49,3	140	60
Skagerak 3-4	49,3	130	60
SwePol	49,4	150	500
NordBalt	49,4	150	500
Estlink 1	49,5	0...50	0
Konti-Skan 1-2	49,5	150	50
Kontek	49,5	50	100
Baltic Cable	49,55	150	500
Konti-Skan 1-2	49,6	150	100
Estlink 2	49,7	0...50	3000
Konti-Skan 1-2	49,8	150	300
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Konti-Skan 1-2	50,3	150	100
Kontek	50,5	50	100
Konti-Scan 1-2	51,0	150	50
Baltic Cable	51,0	50	500
SwePol	51,0	60	500
NordBalt	51,0	60	500
Skagerak 3-4	51,0	240	60

3.2 Start-up of production

Automatic frequency-controlled start-up of production is carried out to increase production in the power system during *operational disturbances*. In the Nordic synchronous area, the only start-up of production is the gas turbine in Sweden starting up 800 MW in three stages of 0.1 Hz in the area 49.7-49.5 Hz.

3.3 Load shedding

If a frequency drop cannot be curbed by the regulation of DC installations and the frequency continues to drop, automatic *load shedding* will occur. The load shedding (LFDD) shall be activated in all the countries in the Nordic synchronous area in a 4-step scheme shedding 20 % of the load in 5% steps activating at 48,8 Hz, 48,6 Hz, 48,4 Hz and 48,2 Hz. In addition, there will be some load shedding activated at 48,0 Hz. This amount may differ between the TSOs.

3.4 Disconnection of lines

Frequency controlled disconnection of the Öresund link (DK2 – SE4) occurs at f < 47.0 Hz in 0.5 s or f < 47.5 in 9 s.

3.5 Stop ramping

If the frequency is below 49,92 Hz and NordBalt is ramping out of the synchronous system, the ramping will be automatically stopped. Similarly, the ramping will also be stopped if the frequency is above 50,08 Hz and NordBalt is ramping into the synchronous system.

If the frequency is below 49,85 Hz and SwePol is ramping out of the synchronous system, the ramping will be automatically stopped. Similarly, the ramping will also be stopped if the frequency is above 50,15 Hz and SwePol is ramping into the synchronous system.

4 System protection activated by voltage deviations

4.1 Sweden constraint 4

The *System protection* will regulate down the transmissions on three DC links to the continent when the voltage in southern Sweden falls below 390 kV. In doing so, constraint 4 will be relieved immediately in the event of an *operational disturbance*. When *system protection* is in operation, a higher level of transmission will be allowed in constraint 4 (2/3 of the *emergency power* intervention). The increased capacity in constraint 4 may only be used when consumption south of constraint 4 is less than 4,500 MW. *System protection* obtains the measured values from seven substations: Breared, Hallsberg, Hedenlunda, Hjälta, Kilanda, Tenhult and Sege.

The criterion for the activation signal of *system protection* is that the voltage in one of these seven points goes under 390 kV for 4 seconds. Upon activation, there will be a power change of 200 MW northbound for Baltic Cable (BC emergency power control entry 3), 250 MW northbound for Kontek, and 300 MW northbound for the SwePol Link (SwePol emergency power control entry 4). For the SwePol Link to become activated, it is also necessary that the voltage at Stärnö is lower than 415 kV.

The Kontek power change will only be initiated if the Øresund flow towards Sweden is below 1400 MW and the northbound flow in the central part of the DK2 grid is below 1700 MW. This is implemented in system protection of Energinet.

4.2 Southern Norway

In Norway, there is *system protection*, which is voltage-controlled. The Skagerrak cables have *emergency power* regulation which is controlled by local voltage measurements at Kristiansand. A low voltage of 275 in 0,8 s results in 200 MW reduced flow towards Denmark within 2 seconds on Skagerrak 1&2 and 270 kV in 0,8 s gives 200 MW reduced flow towards Denmark within 1 second on Skagerrak 3&4.

5 System protection activated by one or more relay signals

5.1 Denmark

5.1.1 Ishøj east, DK2

The purpose of this system protection is to protect the three lines leading out from AVV_400 in case one line is disconnected and another trips. The system protection will reduce the production on AVV B02 steam turbine to 150 MW and disconnect the gas turbines.

5.1.2 Hovegård North, DK2-SE4

This system protection has been installed to protect the two 132 kV Øresund cables if the last 400 kV line is disconnected. The system protection is only armed if one of the 400 kV cables are disconnected and the Øresund power flow is above certain thresholds. If armed, it can be activated by tripping of one of the 400 kV lines connecting DK2 to SE4. The system protection consists of four pre-fault power flow scenarios:

- Øresund flow direction SE4 between 350 MW and 540 MW: 300 MW power flow change on Great Belt1 direction DK1.
- Øresund flow direction SE4 above 650 MW: 600 MW power flow change on Great Belt1 direction DK1.
- Øresund flow direction DK2 above 150 MW: 250 MW power flow change on Great Belt1 direction DK2.
- Øresund flow direction SE2 above 150 MW and Great Belt1 flow direction DK2 above 350 MW: 250 MW power flow change direction DK2 on both on Great Belt1 and Kontek.

The regulation speed is 500 MW/s for Great Belt1 and 100 MW/s for Kontek. HVDC reversal of power direction is allowed.

5.1.3 Hovegård South, DK2

The three 400 kV lines leading south from Hovegård 400 kV station (DK2) are equipped with system protection to protect the 400 kV, 220 kV and 132 kV grid from overload. If one 400 kV line is disconnected and the grid power flow is above certain thresholds, and another 400 kV line trips, the system protection is activated. The system protection consists of three pre-fault power flow scenarios:

- Southbound power flow above 1000 MW: Runback of Great Belt1 to 150 MW and activation of weak grid mode.
- Northbound power flow between 1000 and 1300 MW: 300 MW power flow change on Great Belt1 direction DK1.
- Northbound power flow above 1300 MW: 600 MW power flow change on Great Belt1 direction DK1.

The regulation speed is 500 MW/s for Great Belt1. HVDC reversal of power direction is allowed.

5.1.4 Bjæverskov West, DK2

The two 400 kV lines leading west from Bjæverskov 400 kV stations (DK2) are equipped with system protection. The purpose is to protect the 132 kV grid from overload and secure stable operation on Great Belt1 HVDC. If one 400 kV line is disconnected and the other one trips, Great Belt1 infeed to DK2 will be reduced to 150 MW and weak grid mode is activated. The regulation speed is 999 MW/s.

5.1.5 Kriegers Flak transformer, DE-DK2

If one of the 500 MVA 400/220 kV transformers connecting the Kriegers Flak offshore system to DK2 is tripped and the power flow to DK2 is above 650 MW a runback to 240 MW on the Danish Kriegers Flak wind farm is initiated. This can result in a maximum power change into DK2 of 370 MW. The down regulation speed of the wind farm is 60 MW/s.

5.1.6 Kriegers Flak Master controller, DE-DK2

The Kriegers Flak offshore system between DK2 and Germany (called Combined Grid Solution) is equipped with automatic load flow control (master controller) controlling the agreed power exchange at the offshore border and keeping the loading of components below their limits. The offshore grid is operated without N-1 security. This is done by first controlling the power flow on the HVDC back-to-back converter in Bentwisch(Germany) and secondly curtailing offshore wind generation in either the Danish or German part of the system depending on the location of the grid constraint and the power flow direction. If an offshore 220 or 150 kV cable trips the power flow change into DK2 can be up to 350 MW depending on the prefault power flow. The regulation speed is slow, 100 MW/min., due to the large thermal time constants of the offshore cables.

5.1.7 Fraugde-Landerupgård, DK1

The two 400 kV lines west of 400 kV station Landerupgård (DK1) is equipped with system protection to protect the 150 kV grid. If one line is disconnected and the other one trips and the Great Belt1 power flow is above 25 MW a runback of Great Belt1 is initiated. The regulation speed is 999 MW/s.

5.1.8 Kassø-Landerupgård, DK1

The 400 kV line south of 400 kV station Landerupgård (DK1) is equipped with system protection to protect the 150 kV grid and ensure voltage stability when the regions 400 kV connection to Germany is lost. If the line trips, the flow on the line is above 50 MW and the flow on Great Belt1 is above 250 MW a runback of Great Belt1 to 250 MW is initiated. The regulation speed is 999 MW/s.

5.2 Sweden

5.2.1 Production shedding for limiting overloads on lines

System protection carries out the shedding of hydropower production in northern Sweden via remotely transmitted signals from activated protection functions. Total extent of approx. 1,600 MW of installed power. Upon disconnection of lines in constraint 1, there is a risk that other lines will become overloaded. The *system protection* will disconnect production so that the lines will be relieved. The signals originate from Grundfors, Betåsen, and Hjälta and are sent to stations northwards. The setting of the automated equipment is adapted to the state of operation.

The *system protection* also includes a link with Norway so that the loss of a link between Porjusberget and Ofoten will disconnect production in northern Norway.

In case of loss of the 400 kV line between Midskog and Järpströmmen or loss of the 400/220 kV transformer in Järpströmmen, the system protection will disconnect the generators in Järpströmmen and the 220 kV line Järpströmmen-Juveln-Olden-Stensjön in order to avoid overloading the 220 kV grid between Midskog and Järpströmmen.

The loss of Midskog-Järpströmmen line will also lead to disconnection of the 400 kV line Järpströmmen-Högåsen-Nea (in Norway) and a signal is sent to Norway for load shedding in NO3 (in case of export from SE2 to NO3).

The loss of the 400 kV line Järpströmmen-Högåsen-Nea (in Norway) will result in load shedding in NO3 (in case of export from SE2 to NO3).

5.2.2 The West Coast constraint

During imports from Poland, Germany, Zealand and Jutland and a high level of production at Ringhals, simultaneous to exports towards Norway, there is a risk of overloads on the remaining line in Västkustsnittet in the event of a long-term fault on one of the lines. To protect against overloads, there is system protection that, in the event of the loss of Kilanda-Horred or Kilanda-Stenkullen and with transmissions in excess of 500 MW in the northern direction in Västkustsnittet, makes a power change on Konti-Skan 2 down to 0 MW or at 300 MW against Western Denmark based on the selection.

This *system protection* does not provide increased capacity, rather it increases the *system security*. To Eastern Denmark, there is a channel that is activated by system protection and makes a power change of 300 MW direction DK1 on Great Belt1, given that certain operational criteria have been met. The Great Belt power change will only be initiated if the flow on Øresund towards Sweden is above 1000 MW.

In addition, *system protection* protects the underlying 130 kV network against overloads in conjunction with exports on Konti-Skan. If Konti-Skan 2 becomes isolated from the grid but remains connected to the 130 kV network, a signal that controls the exports down to 0 MW is sent, when the regional network cannot supply power both to the Gothenburg region and for exports on Konti-Skan 2, if the supply from the grid is lost in Lindome. During imports, Konti-Skan 2 supply to the Gothenburg region is enhanced for the same situation and remains connected.

Alongside these *system protection* means, there is a "Last Line" protection that disconnects Konti-Skan 1 if contact with the 400 kV network is lost.

There is system protection for protecting the 130 kV network Lindome against overloading, to be introduced when the connection Stenkullen-Strömma or Strömma-Breared is not in operation.

During a fault on the remaining line, system protection will automatically disconnect the Lindome transformers.

It shall be noted that the power change into DK1 shall respect the reference incident of DK1 of 700 MW. The maximum possible power change into DK1 by this system protection is 600 MW (300 MW from Konti-Skan and 300 MW from Great Belt).

5.2.3 Sege

In the event of a relay protection function which disconnects the remaining line in Sege, system protection activates the disconnection of Baltic Cable. System protection is activated irrespective of the direction of transmissions on Baltic Cable.

5.2.4 Loviseholm for the Hasle constraint

During high export levels from southern Norway to Sweden, there is a risk that the loss of a line can bring about overload, voltage or stability problems.

If the total power flow of Halden - Loviesholm and Hasle - Borgvik towards Sweden is larger than 1,200 MW and Loviseholm - Skogssäter is lost, the transformer in Loviseholm will be disconnected to protect the system.

5.2.5 NordBalt

In the event of a relay protection function which disconnects one of the 400 kV lines to the station Nybro, the connection point of NordBalt, NordBalt will be reduced to 0 MW, depending on which of the 400 kV lines that is disconnected and the direction of power transfer on NordBalt.

5.2.6 East-west flow

In the event of a relay protection function which disconnects on of the following lines Hamra - Åker, Åker - Hedenlunda, Hall – Hedenlunda, Hedenlunda – Glan – Kolstad or Hedenlunda – Glan – Kimstad and the current on that line is above a predefined level before the fault, EPC on Konti-Skan and Fenno-Skan 2 will be activated. Konti-Skan will change 300 MW towards Sweden. Fenno-Skan 2 will change 400 MW towards Finland.

5.3 Norway

5.3.1 Hasle and Flesaker constraint (PFK), NO2/NO1 – SE3

During high export levels from southern Norway to Sweden, there is a risk that the loss of a line can bring about overload, voltage or stability problems. In the event of critical losses, the *system protection* must relieve the constraints by means of automatic *production shedding* at Kvilldal, Sima, Aurland, Tonstad, Tokke, Vinje, Oksla and Songa. The maximum permissible *production shedding* is 1,200 MW and activation will occur as a result of the following events:

Loss of Sylling-Tegneby, Tegneby-Hasle, Hasle-Borgvik, Rød-Hasle, Hasle-Halden, Halden-Loviseholm, Loviseholm-Skogssäter, Skogssäter-Kilanda, .

If the loss of the line Ådal-Frogner is critical, system protection that automatically disconnects production in Aurland and/or Sima can be activated.

The *system protection* is also partly described under section 4.2.6.

5.3.2 Nordland constraint 1 (PFK), NO4- SE1

In the event of a large power surplus in northern and central Norway, there is a risk of *network collapse* in the event of losing critical lines. The *system protection* must rapidly relieve the constraint by means of automatic *production shedding* or through network division so that the *surplus area* is separated from the rest of the *synchronous system*. The largest permissible *production shedding* is 1,400 MW.

The *system protection* will be activated by the following events:

- The loss of Ofoten-Ritsem, Ritsem-Vietas, Vietas-Porjusberget, Porjusberget – Harsprånget, Porjusberget-Grundfors, Ofoten-Kobbvatnet, Kobbvatnet-Salten, Salten-Svartisen, or Svartisen-Rana-Nedre Røssåga.

The *system protection's* setting will depend on the operational situation and can result in *production shedding* at Vietas, Ritsem, Kobbelv and/or Svartisen. Loss of the lines Ofoten-Ritsem-Vietas-Porjusberget, Porjusberget – Harsprånget or Porjusberget-Grundfors might also lead to network division south of Kobbelv and/or network division between Norway and Finland. The *system protection* is also described under section 4.2.1.

5.3.3 Nordland constraint 2 (PFK), NO4/NO3-SE2

In the event of a large power surplus in central Norway, there is a risk of *network collapse* in the event of losing critical lines. The *system protection* must rapidly relieve the constraint by means of automatic *production shedding*. The largest permissible *production shedding* is 1,200 MW.

The *system protection* might be activated by the following events:

- The loss of one of the 300 kV connections Nedre Røssåga-Marka-Trofors-Tunnsjødal-Verdal-Strinda-Klæbu or 420 kV Klæbu-Nea-Järpströmmen-Midskog, or 420 kV Nedre Røssåga-Tunnsjødal-Namsos-Ogndal-Verdal-Klæbu-Surna-Viklandet or 420/300 kV Nedre Røssåga transformer or 420/300 kV Klæbu transformer.

The *system protection's* setting will depend on the operational situation and can result in *production shedding* at Svartisen, Harbaksfjellet, Kvenndalsfjellet, Storheia, Roan (Harheia and Einarsdalen) and/or Sørmarksfjellet.

5.3.4 System protection for load shedding

System protection which disconnects 470 MW SU4 or 180 MW SU3 of industrial loads in the event of the loss of one or two 300 kV lines adjacent to Møre or in the event of the loss of at least one of the 420 kV lines Midskog-Järpströmmen-Nea- Klæbu-Surna-Viklandet. The network supplies general consumption and important industrial centres in Nord-Vestlandet.

5.3.5 Sørlandsnittet (PFK and HVDC control)

During abundant exports from Southern Norway to Denmark and with simultaneous low local production, there is a risk of loss of a line, which can lead to overload or voltage problems. During a critical loss of a line, the *system protection* will relieve the constraint through automatic downward regulation of the Skagerrak HVDC line. The *system protection* measures overload on the 300 kV lines at three stations. The *system protection* regulates 400 or 600 MW of exports down on Skagerrak 34 during 1-2 s.

During abundant imports to Southern Norway from Denmark and with simultaneous high local production, there is a risk of loss of a line, which can lead to overload or voltage problems. During a critical loss of a line, the *system protection* will relieve the constraint through automatic downward regulation of the Skagerrak HVDC line or PFK at Tonstad. The *system protection* measures overload on the 300 kV lines at two stations and overload on the 420 kV at one station. The *system protection* regulates 300 or 600 MW of imports down on Skagerrak 34 during less than 1 s and/or regulates production down at the Tonstad power plant (4 x 160 MW available).

During high exports or in the event of an outage in Southern Norway, there is system protection that, in the event of the loss of the 420 kV line Kristiansand-Brokke-Holen or the 420 Rød-Grenland-Bamble-Arendal-Kristiansand, reduces the exports by 400 or 600 MW on Skagerrak. During import in the event of loss of the 420 kV line Kristiansand- Brokke-Holen or the 420 Rød-Grenland-Bamble-Arendal-Kristiansand, the system protection reduces the imports by 300 or 600 MW and/or reduces production at the Tonstad power plant (4 x 160 MW installed power).

5.3.6 NSL

During high exports and imports from/to Southern Norway to/from Great Britain, a loss of a line can lead to overload problems. In critical line losses, system protection shall relieve the lines by means of automatic downward regulation of the NSL HVDC link. System protection measures the load on several lines in Southern Norway. System protection shall reduce the exports/imports on NSL by 600 MW within 1.0 s or 1200 MW within 1.7 s.

5.4 Finland

5.4.1 Frequency regulation with automated systems on the HVDC Fenno-Skan link

The *system protection* can be used when the AC connection between Finland and Sweden is broken to control the frequency when Finland is in island operation.

5.4.2 Power modulation for Fenno-Skan (Power modulation control)

The *system protection* can be used to attenuate large power oscillations between the countries. Uses the frequency difference between Sweden and Finland as a signal and modulates the power ± 100 MW. Not in service at the moment.