Chapter 9
Operation and Maintenance: Reliability

Contents

9.1 Operation of Submarine Cables

After commissioning, submarine power cables are expected to work troublefree for decades. The cable operator can contribute to a long useful life and a high reliability of the cables by some maintenance actions. This chapter explains what the cable operator can do to improve the availability.

9.1.1 Common Measures for All Kind of Submarine Power Cables

The cable operator must protect the cable from a number of hardships, such as overvoltage, overheating, external violence, fatigue, etc. This requires an active involvement and the establishment of maintenance plans for the cable system. In most cases, a simple instrumental monitoring is sufficient.

Overvoltage can be avoided by a system analysis prior to system design. Surge arresters with appropriate protection levels should be used, especially when the

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submarine cable is connected to overhead lines. Surge counters should be checked regularly in order to detect anomalies in the power system behavior. Temporary system overvoltage due to strong generation (e.g. in OWP) should be monitored carefully and mitigation strategies considered.

The risk of overheating can arise even if the cable is run within its design limits. Seafloor conditions can alter within months, and the cable route can be covered with additional thick layers of sediment. This reduces the heat flow from the cable, which leads to cable temperatures higher than expected. Also, other services such as pipelines, flow lines, other power cables, etc., may suddenly turn up in the vicinity of the power cable. The cable operator should develop strategies to detect this type of thermal hazards:

- Disseminating knowledge of the existence of the cable to authorities, infrastructure developers, utilities etc.
- Watch out for construction activities at the cable sites
- Study bathymetric updates from survey companies, marine authorities and professional associations
- Check and compare satellite photographs in regular intervals.

The thermal conditions along the cable route can be monitored with a DTS (Distributed Temperature measurement System). Adverse conditions can be detected, and relieving action can be launched.

Free spans in the cable route should be checked from time to time to detect a possible enlargement. Too long free spans can easily cause vibration, chafing, fatigue, and cable failures. Free spans can be stabilized with additional rock-dumping, or with mid-span guy lines. Another possibility to improve the vibration characteristics of free spans is the subsequent application of VIV suppression strakes.

A number of active measures can be taken to avert external damage to the cable. In Chap. 7, measures for the active post-lay cable protection are described. They range from information campaigns for the fishing community to repeated share of cable position data to authorities, nautical agencies, etc. Active ship traffic monitoring allows for warning of vessels, should these come too close or try to anchor too close to the cable route.

The cable operator can monitor the character and frequency of vessel traffic and fishing activities along the route of the cable. If the vessel traffic increases in size or numbers, the cable operator may consult marine authorities in order to discuss methods to divert traffic from the area.

9.1.2 Instrumentation

Taking active control of the operation of a submarine power cable may increase the availability and profitability of the cable link. Suitable instrumentation is available to do this.

9.1.2.1 DTS

The Distributed Temperature Measurement System (DTS) is an optical fibre-based temperature sensor incorporated into the power cable, or installed alongside the power cable. Such a system is able to monitor the temperature along the power cable. A land based monitoring unit evaluates the optical signals and displays a temperature profile over the cable length.

Hot-spots and cold-spots, and other irregularities along the cable route can be detected with DTS. By comparing DTS printouts from subsequent years, it is possible to detect sediment wash-away at the particular location. If a submarine cable is exposed in free spans or by wash-away of sediment it should be considered to take advantage of the situation and fly an ROV along the cable to inspect it for damages and corrosion. Submarine power cables that are not buried should be inspected regularly by divers or ROV to confirm their status or changes in their environment.

Most DTS have built-in ODTR capabilities to detect and localize fibre damage. But DTS can be used even if everything is running smoothly.

The temperature profiles recorded from this system can be evaluated to perform a dynamic cable rating. In contrast to the conventional static "Rated Power", the system is able to calculate the ampacity of the link by taking into account the actual ambient conditions. The cable operator can take advantage of the ampacity changes over the seasons of the year. Furthermore, dynamic rating can exploit thermal reserves in the cable system for temporary overloads. The operator of links designed for the purpose of power trading may use this system to generate extra income without putting the cable integrity at risk. Dynamic rating systems are also known under the acronyms CLPS or RTTR.

If the power cable is equipped with optical fibres for data transmission, these can be used for ad-hoc distributed temperature measurements.

9.1.2.2 CDVC

The Cable Dependent Voltage Control, designed for mass-impregnated d.c. cables, is a control function resident in the HVDC converter station. At reduction of power demand, the system reduces temporarily the system voltage without limiting the transmission capacity. Doing so, the electric stress in the cable insulation is reduced when the cable is cooling down. The voltage reduction has the potential to increase the electric life of the cable. When full power is required again, the voltage returns to rated.

9.1.2.3 Partial Discharge Monitoring

Partial discharge (PD) monitoring of power cable systems has achieved a sophisticated level. Defects, inhomogenities and other flaws can be evaluated with on-line PD detection systems. PD activities on a particular spot in the cable link may indicate the presence of a small damage in the cable insulation system or in a cable joint.

Modern PD measurement systems are getting increasingly powerful in discrimination of PD signals and their relevance for the future cable life. Still, it is extremely difficult to monitor a longer stretch of submarine power cables from the shoreline as PD signals tend to be attenuated after only a few kilometres of travel through the cable.

Furthermore, there is the great question about what happens if the system detects an increased PD activity in a particular joint or cable location out there. Would the TSO manager decide the interruption of the cable link for repair of a suspicious cable portion? Or would he/she prepare a repair operation but wait for the breakdown that may not happen?

9.1.3 Mass-Impregnated Cables and XLPE Cables

Mass-impregnated and extruded cables, also called solid cables (cf. Chap. 2), are maintenance-free. This is also valid for the submarine joints belonging to these cable types. Cables with solid insulation have no free oil volume that needs to be pressurized from the shore stations. The terminations require only a small pressure vessel to accommodate the oil expansion inside the termination. The monitoring sensors for pressure and oil level can be connected to the substation SCADA system. Too low or high pressure would cause a tripping of the link.

XLPE insulated a.c. cables are sometimes terminated directly into GIS substations. Not all, but some GIS cable terminations have small amounts of insulation oil (mineral oil, polyisobutene oil or silicone oil) calling for level/pressure monitoring. The maintenance requirements are identical to those applicable for equivalent terminations for land cables.

9.1.4 LPOF, SCOF and SCFF Cables

Fluid-filled (FF) and oil-filled (OF) cables require the monitoring of the oil-pressure feeding system. Since the performance of these cables is critically depending on the prevailing oil pressure, it must be monitored on-line. A loss of oil pressure indicates a cable damage calling for immediate attention. The pressure monitoring can be connected to the substation SCADA system. The cable link will be tripped if the pressure falls under a certain limit.

Sufficient amounts of degassed dielectric fluid must be available in the feeding station in order to maintain a positive oil pressure also in the case of a cable leakage. As leaks may be large and weeks may elapse until the cable can be sealed, it should be considered to keep an extra stock of cable oil not too far from the termination. Cable operators of one region can cooperate in this issue, as cable oils from different cable systems usually are compatible.

9.1.5 Cable Terminations

The proximity of many submarine power cable terminations to the sea may cause severe salt layer deposits on the insulators calling for a regular cleaning schedule. Some cleaning can be done under energized lines. Some termination insulators rely on the hydrophobicity of polymeric materials or coatings. The remaining hydrophobicity should be tested regularly, e.g. according to visual tests suggested by STRI [1] and set forth in an IEC specification [2].

All terminations erected close to shore or on marine platforms must be checked regularly for corrosion. Especially galvanic corrosion between different metals can be onerous.

9.2 Reliability of Submarine Cables

Submarine power cables are often a special asset in the basket of TSOs and might deserve closer attention. The operating utilities are very much interested in a trouble-free operation because repair is expensive and can be cumbersome. Also, submarine power cables are often not a part of a meshed network with large redundancy. On land, the power flow blocked by a cable failure can most often be rerouted through other paths of the grid. In contrary, submarine power cables often have no redundant grid for back-up. A submarine cable failure can darken islands or oil/gas production platforms, or cut the revenues from offshore wind farms. A failure in submarine cables connecting self-sustaining grids (such as HVDC links between countries) would not black-out cities, but would deprive the owners of large revenues from power trading. For this reason, the reliability of submarine power cables is an important aspect of each business model and has strong influence on the cable design.

Unfortunately cable operators are somewhat reluctant about reporting failure statistics. A number of journal articles were published in the 1970s and 1980s reporting on experiences from large submarine cable links including accounts of failure modes and repair methods. In the last decade reports of this kind have become astonishingly scarce. Owing to the excellent work of the Cigré Study Group B1 (erstwhile SC 21), cable operators have the possibility to report cable experiences and failures confidentially without annoying the shareholders.

9.2.1 The Cigré Studies

The Cigré organisation (Cigré=Conseil International des Grands Réseaux Électriques) has established a working group that regularly collects data on submarine power cable reliability. In 1986 it published an often-cited compilation on experiences from thousands of kilometres of submarine power cables [3]. The

Table 9.1 Failure rates for submarine power cables > 60 kV expressed in (failures/(year×100 circuit kilometres))

	Internal origin failures	External origin failures	All failures
a.c. HPOF cables	0	0.7954	0.7954
a,c, LPOF cables	0	0.1189	0.1189
a.c XLPE cables	0	0.0706	0.0706
d.c. MI cables	0	0.1114	0.1114
d.c. LPOF cables	0.0346	0	0.0346

study covers experience from 1950 to 1980. It arrives at a failure rate of 0.32 failures/year/100 cable kilometres. Only a small fraction of the cable kilometres considered in this failure rate are protected. Today, since the protection rate of submarine power cables is considerably higher, and survey methods, cable design, and installation methods have developed enormously, the failure rate is expected to be much lower.

According to the 1986 Cigré study 82% of the failures occurred in the cables and 18% in the joints. The dominant majority of the cable faults were caused by external violence, while the joint failures mostly were caused by poor engineering, installation or maintenance.

The failure rates reported in the 2009 Cigré study [4] are summarized in Table 9.1. Except for HPOF submarine cables (which are used very rarely today), all failure rates are much lower than the 1986 values. The values are related to circuit kilometres. As circuit often comprises two, three or four individual cables, the rate as per cable kilometre would be even lower.

While the ratio of joint failures to cable failures was 0.22 in the 1986 study, this relation changed to 0.095 in the 2008 study. This indicates a much higher relative safety of cable joints in the recent time.

It should be noted that calculated failure rates can be warped by a few notorious cable links, which account for a significant share of the reported failures.

9.2.2 Failure Statistics for Large HVDC Cable Projects

The failure rate calculated from the data given in Table 9.2 is 0.264 failures/year/100 cable kilometres for mechanical faults and 0.0143 failures/year/100 cable kilometres for other failures. "Other faults" means internal faults, such as the failure of the insulation system. It is evident that a few cable systems contribute largely to the failure statistics. In particular, the 1964–1988 Kontiskan 1 suffered many mechanical failures. Without the contribution of the Kontiskan 1 link the failure rate would be only 0.1 failures/year/100 cable kilometres. It is obvious that badly engineered cables or unsuitable installation methods account for the majority of cable failures.

Table 9.2 Failure in some large HVDC cable links as per 1998[5]

Cable project	V [kV]	P [MW]	L [km]	Max depth [m]	Cables [#]	In service year	Service time years	Technical service [km*years]	Mech faults [#]	Other faults [#]
Kontiskan 1	285	300	88	80	1	91	4	352	0	0
Cook Strait	350	185	41	260	3	91	4	492	0	0
Fenno Skan	400	500	200	120	1	89	6	1200	1	0
Konstiskan 2	285	300	88	80	1	88	7	616	0	1
Cross-Chn. 2	250	200	48	60	8	86	9	3456	0	0
Hokkaido-Hon.	250	200	43	550	2	78	17	1462	0	0
Vancouver 2	280	100	32	200	2	76	19	1216	1	0
Skagerrak $\frac{1}{2}$	250	250	128	550	2	76	19	4864	6	0
Vancouver 1	260	100	32	200	3	69	26	2496	3	0
Sardina-Cor.	200	100	118	450	2	67	28	6608	12	0
Kontiskan 1	285	250	87	80	1	64–88	24	2088	44	2
Gotland 1	150	30	93	170	1	54–89	35	3162	7	1
Total			998		27		198	28012	74	4

9.2.3 Definition of Reliability Terms

Reliability terms can be expressed in many different terms. For a correct comparison of information from different sources, it is important to use a well-defined terminology.

Reliability	The probability that a cable is fulfilling its purpose adequately for the period of time intended. The reliability can be described as: $1-(\lambda \times r)/8760$
Availability	A measure of a system's performance in terms of its reliability and maintainability: $1-(\lambda \times r + c)/8760$
Where	λ = number of failures per year r = repair time after failure [hours] c = scheduled outage (e.g. maintenance) [hours/year]
Outage	Period of non/functioning of the system
Forced outage	Involuntary outage as a result of a failure
Failure rate	The annual rate of forced outages associated with failures in the cable
Scheduled maintenance	Annual preventive maintenance as specified by supplier or according to operators own standards
Unscheduled maintenance	All maintenance required that can not be termed annual preventive maintenance

9.2.4 Reliability of Some Specific Submarine Power Cables

A few reports on reliability and availability data can be found in the literature. However, cable operators today are less prone to publish such data. This is a disadvantage to the industry, as investors and insurance companies might need a clearer picture for a fair risk assessment. Here, a few examples are given.

9.2.4.1 Skagerrak HVDC Scheme

The first Skagerrak HVDC cable between Norway and Denmark was installed 1976–1977. The base data are as follows:

Rated voltage	250 kV d.c.
Number of cables	2
Year of commissioning	1976, 1977
Submarine distance	128 km
Largest depth	550 m

The operation statistics for the interval between 1978 and 1984 is reported in [6]. For this pair of cables the availability was always better than 93% during this time span, despite forced outages due to cable failures in two of seven years. In five of seven years the availability was over 95%.

9.2.4.2 Windfarm Export Cable

For a hypothetic OWP export cable the reliability of five different a.c. cable configurations is compared in [7]. Three-core and single-core systems have been investigated for a fictive 60 km 1000 MW power export system. A 275 kV single-core system with seven individual cables (two circuits and one spare cable) was found to have the lowest expected failure rate (0.15 failures per year and cable) (Table 9.3):

Table 9.3 Failure rates for different cable schemes to connect a large OWP

Voltage (kV) cable type	132 3-core	220 3-core	400 3-core	275 SC	400 SC
No of cables for 1000 MW transmission	6	4	2	7 (1 spare)	4 (1 spare)
Failures/year and cable	0.25	0.46	0.67	0.15	0.22

Taken into account the number of cables, the 400 kV system with three single-core cables seems to have the lowest expected number of repairs over lifetime.

9.2.4.3 Fox Islands

Four SC submarine cables were laid between Rockport, Maine, USA, and the Fox Islands in 1976. The 10.4 miles of 34.5 kV circuit replaced on-island diesel generation. The cable system was stricken by 45 faults until decommissioning in 2005 [8]. While the Cigré failure statistics for submarine power cables [1] quote a rate of 0.32 faults per year and per 100 km of cable system, the Fox Island cable counts nine faults per year and per 100 km, and has perhaps the worst reliability record in the world.

9.2.4.4 Long Island

Seven single-core high-pressure oil-filled 138 kV cables were installed under the Long Island Sound and commissioned in 1969. At that time it was the longest oil-filled submarine cable in the world [9]. Eighty percent of the cable route was installed freely on the seafloor, with 275 m spacing between individual cables [10]. Unfortunately, the cable system (called "1385 cable") had an exceptionally bad availability. The operator Long Island Power Authority reports:

> Since being energized in 1969, the existing 1385 Cable had experienced 36 incidents with 58 damages to cables that have resulted in either limited capacity operation or total electrical failures. The causes for incidents included chafing from rock and corrosion, and bottom dragging of grappling hooks or anchors from both small and large vessels. As a result, frequent and extensive maintenance was required for the existing 1385 Cable. Since 1990 alone, the cost of cable repairs has exceeded $45 million.

In spite of the extra spare cable and the spaced installation multiple damages caused 50% capacity drop in extended periods (2–9 months) in the 1970s. The outages were caused mostly by external damages affecting a system already weakened by damages that were caused by severe corrosion. No less than four cables were damaged by a single anchor attack 17 November 2002.

The unlucky cable system is now replaced by a system of three 3C cables with 138 kV rating. Since the new cables are protected by burial six feet under the seafloor, they have much better chances to serve without trouble during many years.

9.2.4.5 Baltic Cable

The Baltic Cable is a HVDC cable connecting Sweden and Germany. The return current is conducted by sea electrodes.

Rated voltage	450 kV d.c.
Number of cables	1
Year of commissioning	1994
Submarine distance	250 km
Largest depth	40 m

The performance data of the Baltic Cable link are summarized in Table 9.4 (Courtesy of Baltic Cable AB, Sweden).

Three failures were reported, one in 1999, 2002 and 2009, resp. This figure calculates to 0.08 failures per year and 100 cable kilometres, which is better than the reported average in both the 1986 and 2009 Cigré studies. The 1999 cable failure led to 3374 h of outage[1] in 1999 and 2000 reducing the availability figure for 2000 drastically. The 2002 failure could be repaired within 8 weeks [11].

Table 9.4 Failure rates for different cable schemes to connect a large OWP

Year	Scheduled unavailability (%)	Forced unavailability (%)	Availability (%)
1995	3.14	0.82	96.04
1996	6.00	1.24	92.76
1997	1.49	1.40	97.11
1998	1.50	2.29	96.21
1999	1.29	7.67	91.04
2000	1.23	30.76	68.01
2001	1.23	0.78	97.99
2002	0.96	14.08	84.96
2003	1.23	0.01	98.76
2004	8.88	0.04	91.08
2005	1.23	0.61	98.16
2006	1.23	1.52	97.24
2007	1.23	0.14	98.63

[1] The cable repair was delayed by vessel unavailability, unsuitable weather and other factors.

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