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VARIABLE SHUNT REACTOR CONTROL FOR VOLTAGE COMPENSATION FOR SUBMARINE CABLE AT OFFSHORE FACILITY

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Abstract—This paper presents the design of a shunt reactor controller (SRC) that provides voltage stability at an offshore and onshore oilfield with a gas and oil separation plant (GOSP) having 90 km submarine cables with different cross sections. There are a total of six shunt reactors (four sets at the 230 kV onshore substation and two sets at the offshore substation). The SRC also coordinates with a utility (UT) transformer tap control to avoid hunting. In addition, the SRC avoids submarine cable overloading.

The paper discusses control philosophy, stepwise methodology, energization, and de-energization sequence for various loading and unloading conditions. The paper also covers different methodologies used to finalize the SRC philosophy to develop the band control strategy and discusses the load-shedding implementation to avoid overloading on submarine cables and UT transmission lines.

The SRC and load-shed control system has been tested and validated using hardware-in-the-loop (HIL) simulation to reduce commissioning challenges.

Index Terms—Shunt reactor controller, submarine cables, voltage stability, shunt reactor control, hardware-in-the-loop.

I. INTRODUCTION

This paper explains the functions of the upgrades made to an onshore/offshore oil field located on the Arabian Gulf. The offshore field is in medium-depth waters with the range of 29 to 52 meters deep. The oil field has gone through the following upgrades.

1. The first Gas Oil Separation Plant (GOSP) was installed in the mid-1970s with a production capacity of 100,000 barrels per day (bpd) of oil and 175 million standard cubic feet a day (Mscfd) of gas [1].
2. The second and third GOSPs were brought into operation in the mid-1990s, bringing the total production capacity of the offshore field to 600,000 bpd of oil and 675 Msfcd of gas.
3. The current crude increment upgrade program added a fourth GOSP that includes 24 oil, water, and gas injection platforms and 200 km of cables [1].
4. The purpose of the new offshore facilities is to increase production to 800 thousand barrels of oil per day (MBCD), remain a reliable oil and gas supplier, and produce 360,000 bpd of ethane and natural gas liquids (NGL) by processing an additional 2.5 billion standard cubic feet per day (Bscfd) of gas produced from the field [1] [2].
5. The NEW-GOSP offshore facility is designed to handle the additional production capacities requirements. NEW-GOSP is a new bridge-connected multiplatform facility that includes the following:
   - Electrical Distribution Platform (EDP)
   - Tie-in platform
   - Production platform
   - Gas compression platform
   - Auxiliary platform
   - Accommodation platform

This paper describes the new Power Management System (PMS) and focuses on the SRC algorithm that is used to control the submarine cable voltage, current, and power factor. Other SRC algorithms can be found in [3]. In addition to SRC, the load-shed system becomes active if the current in incoming overhead transmission line (OHTL) or the submarine cables exceed the allowed limits. The reactor sizes are considered based on the shunt reactor sizing study, which is beyond the scope of this paper.

II. OVERVIEW OF THE ELECTRICAL SYSTEM NETWORK

A simplified single-line diagram of the system under study is shown in Fig. 1. Utility (UT) Substation 1 – 380/230 kV Gas Insulated Substation (GIS) connects with three other 380 kV UT substations, as shown in Fig. 1. UT Substation 2 – 230 kV GIS connects with the Onshore Substation A facility through OHTL 26 km transmission lines.

Furthermore, the New Offshore GOSP platform 230 kV GIS Substation is powered from the 230 kV GIS Substation A located at the onshore plant. Two composite 230 kV subsea cables will be installed from the Onshore Substation A, approximately 90 km to the Offshore Substation B. The 230 kV voltage is stepped down to 69 kV,13.8 kV, 4.16 kV, and 0.48 kV, and is distributed to the plant loads at the Onshore Plant and New Offshore GOSP.

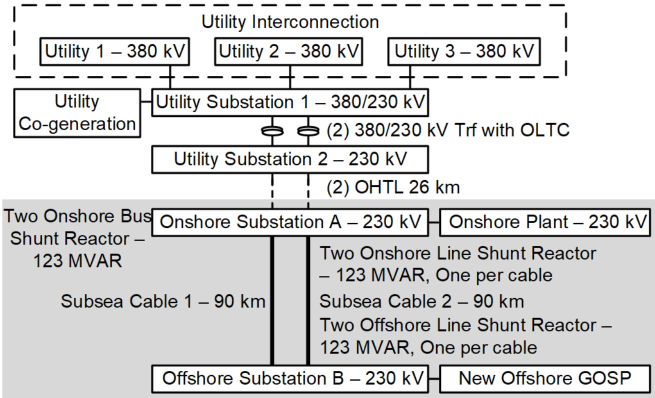

Fig. 1 Overall Single-Line Diagram

A. UT Substation 1 – 380/230 kV and Substation 2 – 230 kV

UT Substation 1 – 380/230 kV connects with other 380 kV UT and co-generation substations. 380 kV is stepped down to Substation 2 – 230 kV GIS through two three winding transformers 380/230/13.8 kV with 750 MVA –15 to 5 percent on-load taps. A 26 km long 230 kV double circuit OHTL is connected to the Onshore Substation A from Substation 2 – 230 kV.

UT transformer on-load tap changers (OLTC) action is not controlled or dictated by the Onshore SRC. The UT transformer OLTC is free to operate whenever the voltage falls outside the set limits.

B. Onshore Substation A – 230 kV

The Onshore Substation A – 230 kV feeds the NEW-GOSP offshore facilities, as well as new and existing onshore loads. Two 123 MVAR shunt reactors are provided for each 230 kV submarine cable at Onshore Substation A (four total).

The shunt reactors are provided for each subsea cable to compensate for the overvoltage related to the large capacitance of the cable. The four onshore shunt reactors have the following characteristics:

1. One shunt reactor is connected to each submarine cable.
2. The other two shunt reactors are connected to the Substation A bus.
3. All shunt reactors are 123 MVAR in size and equipped with OLTC.
4. OLTC range from 40 to 100 percent tap range with 33 taps.

C. 230 KV Submarine Cables Feeding NEW-GOSP Platform Incoming Supply

A double circuit connection is established between the onshore substation and the offshore substation. Each circuit has a short underground cable section (2 • 630 mm^2) for 600 m, short OHTL section (double circuit lattice tower) for 2.1 Km, onshore/offshore transition yard and submarine cable section A, B, C, D and E as shown in Fig. 8. Only Sections C, D, and E are modeled based on length, and they consist mainly of the following:

1. About 30 km of 230 kV 1–3/C 1,000 mm^2 submarine cable. (Sections C and D as shown in Fig. 8)
2. About 60 km of 230 kV 1–3/C 630 mm^2 submarine cable. (Section E as shown in Fig. 8)

D. 230 kV Offshore Shunt Reactors

One 123 MVAR shunt reactor is provided for each 230 kV submarine cable at Substation B (two total). The shunt reactor at the offshore GIS is directly connected to the 230 kV submarine cable. The two offshore shunt reactors have the following characteristics:

1. One shunt reactor is connected to each submarine cable.
2. All 123 MVAR shunt reactors are equipped with OLTC.
3. OLTC range is between 40 to 100 percent tap range with 25 TAPs.

E. Step-down Load Transformers

The onshore/offshore substations have many step-down transformers that feed the loads equipped with OLTC, as listed below.

1. 75/100 MVA, 230/13.8 kV transformers
2. 75/100 MVA, 230/69 kV transformers
3. 30/40 MVA, 69/13.8 kV transformers

III. UNDERSTANDING SUBMARINE CABLE VOLTAGE PROFILE

A. Submarine Cable Voltage and Current Profile

The 90 km submarine cable is best modeled as distributed parameters per km. Fig. 2 shows the long transmission/cable distributed model. The distributed parameters help to have voltage and current equations as a function of distance of the line, as shown in Fig. 3. The maximum and minimum voltage and current location is a function of OHTL/cable loading.

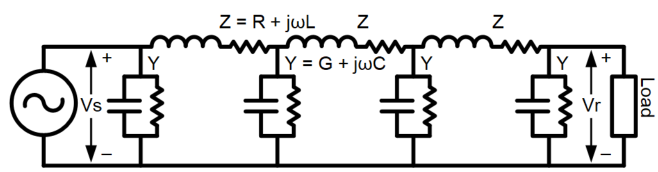

Fig. 2 Distributed Parameters of OHTL

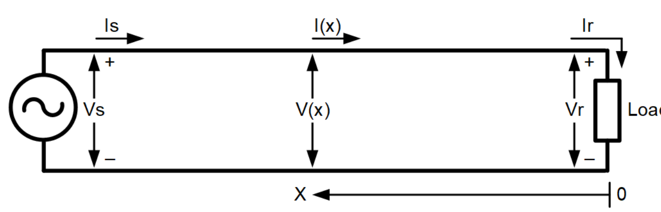

Fig. 3 Voltage and Current as Function of Distance

Equations (1), (2), (3), and (4) summarize the basic equations that can be used to calculate the sending and receiving voltage and current for a long-line model [4] [5], which is used to calculate the voltage and current as a function of distance x measured from the receiving end.

$$\text{Characteristic impedence } Z_C = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{1}$$

$$\text{Propagation constant } \gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{2}$$

$$\begin{bmatrix} V_X \\ I_X \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} = \begin{bmatrix} \cosh(\gamma x) & Z_C \sinh(\gamma x) \\ \dfrac{\sinh(\gamma x)}{Z_C} & \cosh(\gamma x) \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

(3)

when:

$$x = \ell \rightarrow V_X = V_S$$

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} \cosh(\gamma \ell) & Z_C \sinh(\gamma \ell) \\ \dfrac{\sinh(\gamma \ell)}{Z_C} & \cosh(\gamma \ell) \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \tag{4}$$

where:

x	distance measured from receiving end in km [(1)].
R	TL resistance Ω / km
L	TL inductance Henry/km (H/km)
C	TL capacitance Farad/km (F/km)
G	TL conductance Siemens/km
ℓ	Total length of the cable in km
V_r, V_s	sending and receiving end voltage in V
I_r, I_s	sending and receiving end current (A)

[(1)] All the figures in this paper are using the distance from sending end (Substation 2) to receiving end (Substation B), total distance is 26 km + 90 km = 116 km

Fig. 4 shows voltage profile of the combined OHTL and two submarine cables connection as a function of distance measured from Substation 2 to Substation B. The solid line shows the voltage without any shunt reactor at zero-load condition. The dashed line shows the voltage with full size shunt reactors (492 MVAR onshore, 246 MVAR offshore) at full-load condition (250 MW onshore, offshore)

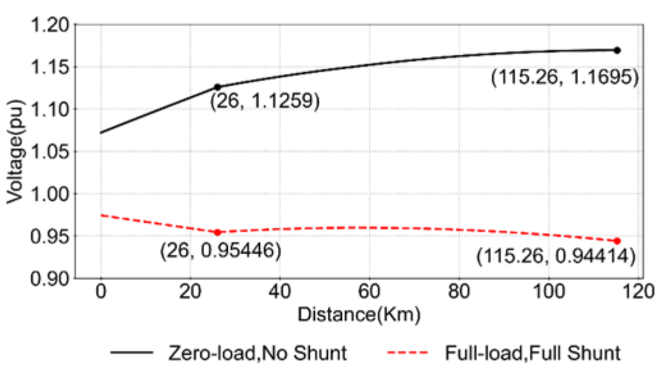

Fig. 4 Voltage Profile Without SRC.

Fig. 5 shows the plots for the zero-load SRC and full-load SRC voltage profiles. The solid line shows the voltage profile with shunt reactor at zero-load condition with SRC. The dashed line shows the voltage with shunt reactor at full-load condition with SRC. Fig. 5 shows that the SRC algorithm, as explained in Section V, keeps the sending and receiving end voltages between 1.01 and 0.99 pu and avoid the overvoltage and undervoltage shown by the full load, full-shunt and zero-load, and no shunt curves.

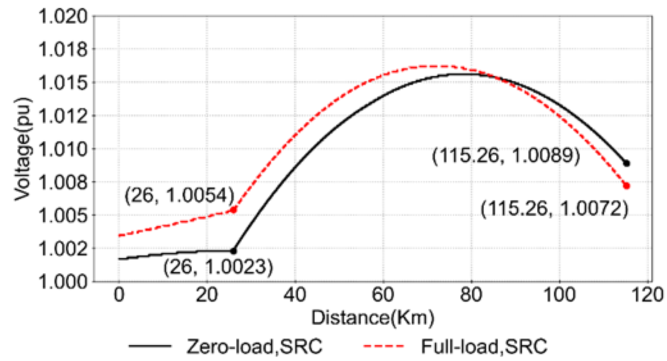

Fig. 5 Voltage Profile With SRC.

Fig. 6 shows the current profile of one submarine cable as function of distance when energizing two submarine cables.

The solid black line shows the current without any shunt reactor at a zero-load no shunt condition. It is a straight line with two different slopes due to different linear charging current of the submarine cable and OHTL segments with maximum current at the sending end of submarine cable equal to 910 A. The dashed line shows the current with full size shunt at full-load condition. The minimum current is 330 A at 68 km. The submarine cable sending end current is 498 A and increases to 724 A after sending end reactor compensation and receiving end current is 498 A.

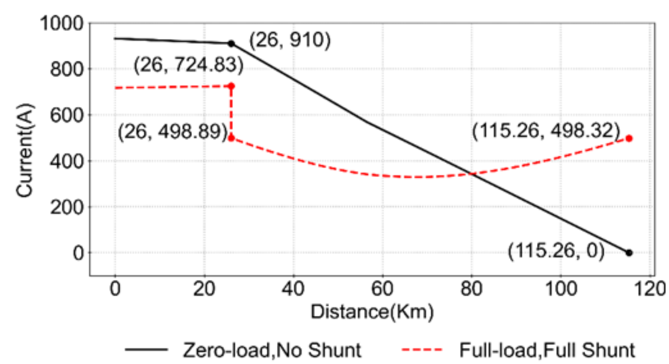

Fig. 6 Current Profile Without SRC

Fig. 7 shows the current profile with SRC. The solid line shows SRC current with shunt reactors at a zero-load condition. The receiving end current is pure inductive current due to the receiving end shunt reactors and start to decrease due to submarine capacitive charging current until it reaches zero at 79 km and starts to increase again till it reaches maximum value of 487 A. It then drops to 2.53 A after sending end reactor compensation and slightly increases due to OHTL charging current. The dashed line shows SRC current with shunt reactor at full-load condition. The minimum current is 310 A at 82 km. The submarine cable sending end current is 632 A after compensation and receiving end current is 417 A.

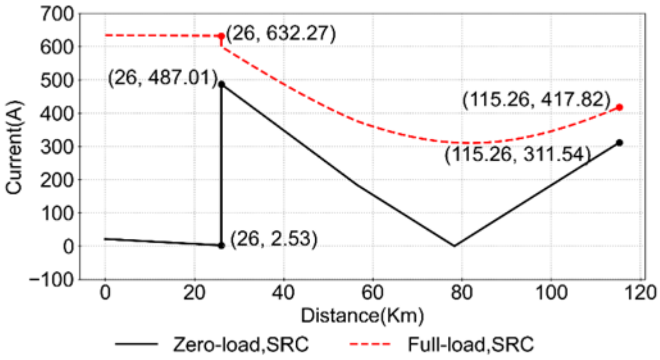

Fig. 7 Current Profile With SRC

B. Submarine Cable Propagation Speed

The propagation speed of an electromagnetic wave along a transmission line is given by (5).

$$v = 1/\sqrt{(L \cdot C)} \tag{5}$$

where:

L is the inductance in H/m

C is the capacitance in F/m

For submarine cable the average speed of propagation for two sections is

$v = 1.19 \cdot 10^{8} m/s$

While the speed for 26 km OHTL is

$v = 2.9 \cdot 10^{8} m/s$

The propagation speed of an electromagnetic wave in OHTL is more than two times the speed in the submarine cable and is close to the speed of light in OHTL.

C. Power Submarine Cable Physical Design

The typical 230 kV submarine cable cross section [6] is shown in Fig. 8. Due to the physical construction of the submarine cable such as the three phases are much closer to each other's compared to OHTL, the shunt capacitance of the submarine cable is much larger than a regular OHTL. Therefore, the charging current and MVAR produced per unit length for the submarine cable connecting Substation A to Substation B is more than ten times the charging current and MVAR produced by OHTL between Substation 2 and Substation A.

D. Ampacity of Power Submarine Cable Design

The ampacity of the submarine cable is a function of the installation condition of the cable and the temperature around the cable. Fig. 9 and Table I shows the information for the oil field. The cable joints are performed in factory before layoff and tested as per standards. Hence the joints are recognized as part of the cable and not an accessory to the cable.

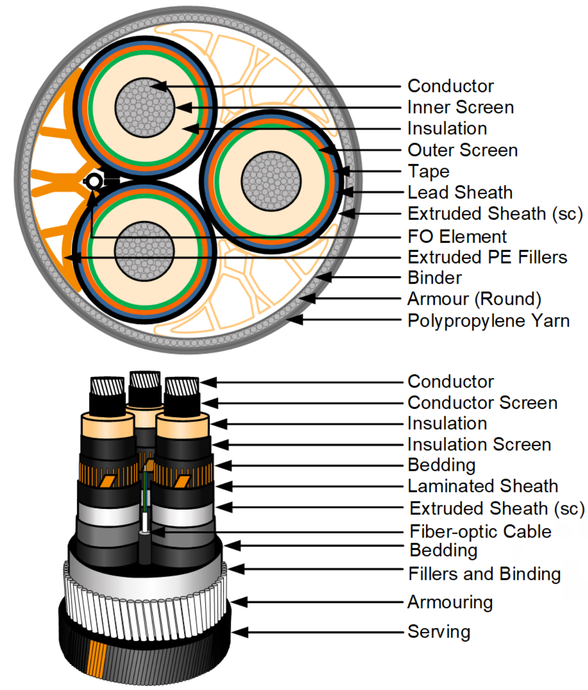

Fig. 8 230 kV Cable Cross Section [6].

TABLE I
CABLE INSTALLATION CONDITIONS AMPACITY

Section	Description	Area (mm²)	Temp (°C)	Ampacity (A)
A	Vertical in air	—	45	—
B	Buried wet sand	—	30	—
C	Buried wet sand	1000	30	844
D	Subsea buried	1,000	30	798
E	Subsea laid	630	30	1,245
F	J-tube- Wet	1,000	30	1,084
G	J-tube Dry	1,000	45	891
H	Vertical in air	1,000	45	935

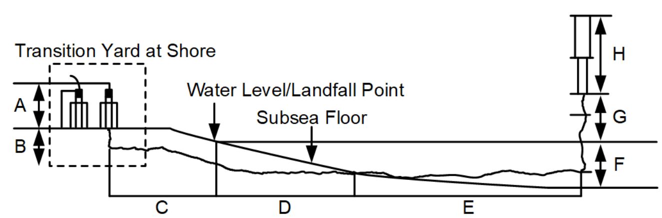

Fig. 9 Cable Installation Condition

IV. LOAD SHEDDING FOR OHTL AND SUBMARINE CABLES OVERLOAD

The Progressive Load Shedding (PLS) system monitors overload conditions for the onshore transmission lines connecting Substation 2 to Substation A and for the offshore submarine cables. If an overload persists on any of the lines or cables for a fixed time, loads are shed sequentially based on priority until the overload condition is cleared. PLS logic implemented in conventional generators [7] is modified to implement sequential shedding of loads if a line or a cable overloads occur.

The PMS PLS monitors the transmission line and submarine cable current separately and continuously checks for overload condition as shown in Fig. 10.

1. The PLS system monitors overload conditions on the onshore transmission lines connecting Substation 2 to Substation A and submarine cable currents.
2. If the current flowing through the line or subsea cable is above the user-settable pickup, then the comparator output becomes high.
3. If the comparator output remains high for a time equal to the user-entered pickup timer setting, then PLS event is asserted.
4. PLS will then shed the first load based on priority.
5. The load-shed trigger is then blocked for a time equal to the maximum reset time before the next load can be shed.
6. After the maximum reset time has elapsed, if the PLS timer output remains high, PLS will shed the next available load based on priority. PLS continues to shed load sequentially if the overload condition persists.
7. PLS sheds load in the onshore substation if the transmission line is overloaded.
8. PLS sheds load in the offshore substation if the submarine cable is overloaded.

When the current flowing through the line or subsea cable drops to less than the user-entered pickup value, the comparator output becomes low and the PLS resets.

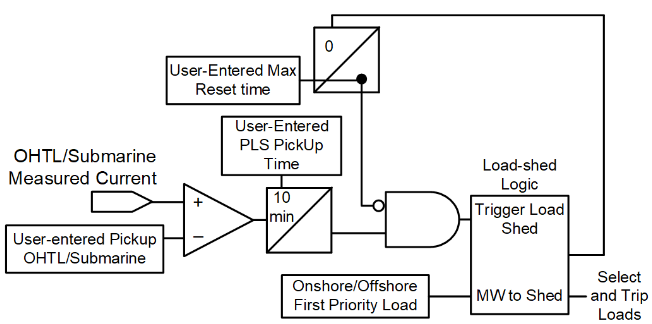

Fig. 10 PLS Logic

V. SHUNT REACTOR CONTROL PHILOSOPHY

A. Step 1: UT 380/230 kV Transformer Tap

For any voltage change in the system, the 380/230 kV UT transformer tap operates first and corrects the Substation 2 voltage within the bandwidth of 99.2 to 100.8 percent. When the 230 kV Substation 2 voltage falls within the bandwidth limit, the UT transformer tap operation stops and then SRC proceeds to next steps.

The above action is achieved by communicating the status of the UT transformer OLTC operation to the Onshore SRC system. If the status of the transformer OLTC is "In Operation," then Steps 2 and 3 will not be initiated. If the status of the transformer OLTC is "Not in Operation," then Steps 2 and 3 will be initiated.

A 20 second time delay is recommended for UT transformer OLTC operation to ride through the voltage drop during large motor direct online starting (DOL) such as gas compressor motor staring and crude shipping motor starting.

A 25 second time delay is considered for the initiation of Steps 2 and 3 to account for the UT transformer OLTC operation time delay. In other words, the SRC will provide the permission for Step 2, 25 seconds after the receipt of the UT transformer OLTC "Not in operation" signal.

B. Step 2: Offshore Shunt Reactor Tap

After Step 1, the offshore reactor tap operates if the system parameters fall outside the set limits and corrects the parameters within the set limits. The limits set for the two modes of operations of offshore reactor are as follows.

1. Voltage Mode:- 230 kV Offshore Substation B Voltage band between 99 to 101 percent.
2. Current Mode:-Current through submarine cable within a band of 775 A and 785 A.

More details can be seen in Fig. 11.The current threshold is set as per Table I and set at 798 A and this is a user-settable value.

Step 4 will be initiated if the Step 2 parameters are within the specified band limit or if the offshore reactor tap reached either maximum or minimum tap.

C. Step 3: Onshore Shunt Reactor Tap

After Step 1, the onshore reactor tap operates (both cable and bus reactor) if the system parameters fall outside the set limits and corrects the parameters within the set limits. The limits set for two modes of operation of onshore reactor are as follows.

1. Voltage mode:- 230 kV Onshore Substation A Voltage band between 99 to 101 percent.
2. PF mode:- PF at UT 230 kV to Onshore Substation A OHTL within a band of +98 (Lagging) to –98 percent (Leading)
3. Reactive Mode:- Reactive power at UT 230 kV to Onshore Substation A OHTL is within the band limits in light load conditions

More details of the SRC algorithm for Step 3 can be seen in Fig. 12.

Step 4 will be initiated if the Step-3 parameters are within the above specified band limit, or if the onshore reactor tap reached either maximum or minimum tap.

D. Step 4: Onshore and Offshore Power Transformer Tap

Step 4 gives permission to onshore/offshore transformers OLTC to control the secondary voltage. After Step 2 and Step 3, 230/13.8 kV, 230/69 kV and 69/13.8 kV transformers OLTC at offshore/onshore substations operate to maintain the secondary voltage of the transformers between bandwidth of 99.6 to 100.4 percent. If Step 1, Step 2, and Step 3 are not met, Step 4 permissive will be blocked. The paper will not cover the details of Step 4.

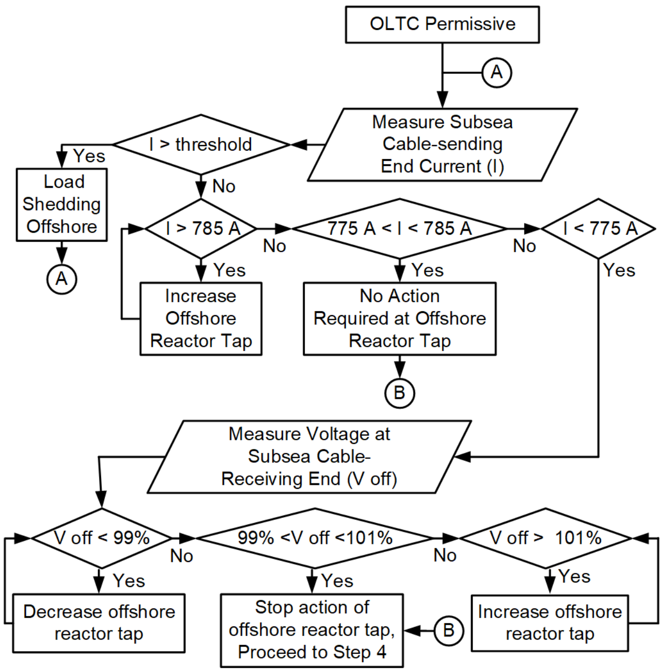

Fig. 11 Step 2: Offshore Shunt Reactor Tap Flowchart

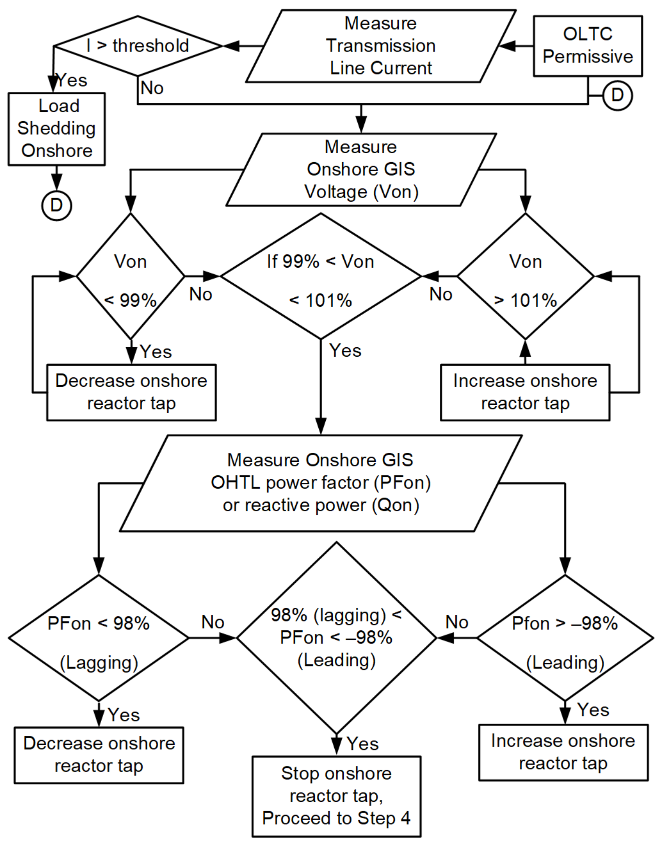

Fig. 12 Step 3: Onshore Shunt Reactor Tap Flowchart

E. Additional Algorithm

The following are the additional logic that is implemented in the SRC algorithm but out of scope for this paper.

1. Tap equalization: equalizing the onshore and offshore reactors tap positions to have equal tap positions if both cables are energized.
2. Hunting detection: hunting scenarios occurs when offshore current and voltage modes, or onshore voltage and PF/MVAR modes conflict with each other's. Reactor taps starts cycling up and down until hunting is detected. SRC control is stopped.
3. Hunting reset: automatic enabling of SRC based on power system status changes after hunting detection.

VI. CASE STUDY AND RESULTS

All the tested cases are performed with the following preexisting topology.

1. Onshore Substation A 230 kV GIS with two 380/230 kV UT transformers.
2. Two 230 kV OHTL between Substation 2 and Substation A.

The following energization sequence is performed for all the test cases.

1. Energization of first and second 230 kV subsea cable along with two cable reactors at nominal tap (Position 1) at sending and receiving ends.
2. Energization of one 123 MVAR bus reactor at nominal tap with each cable energization.

Refer to Table II for a description of the labels used in Table III, Table IV, Table V, and Table VI, as well as Fig. 13, Fig. 16, Fig. 19, and Fig. 22 in this section.

TABLE II
REACTOR AND SEC OLTC TAP SUMMARY

Table Label	Figure Label	Description
Tap R	R1	Cable 1 Receiving end reactor tap pos
	R2	Cable 2 Receiving end reactor tap pos
Tap S	S1	Cable 1 Sending end reactor tap pos
	S2	Cable 2 Sending end reactor tap pos
	SB1	Cable 1 Sending end bus reactor tap pos
	SB2	Cable 2 Sending end bus reactor tap pos

A. Energizing Single Submarine Cable at 380 kV

1. Start up the energization of first submarine cable. Receiving end breaker is still open.
2. After 6 minutes, Cable 1 receiving end breaker is closed with light load and offshore substation is energized.
3. After 12 minutes, the full load is added on onshore and offshore. SRC Offshore is in current mode.
4. After 21 minutes, loading is reduced to zero on onshore and offshore.

Refer to Table III and Fig. 13 for a summary of all tap positions and voltage and current satisfactions. 1L is one step down and 1R is one step up for the UT OLTC.

Table III shows that the offshore voltage is not maintained in the desired band of ±0.01 at the full-load condition since SRC is controlling the submarine cable current that has high priority over the voltage. At 12 minutes the SRC is in current mode and the receiving end voltage is outside band. Also at 6 and 21 minutes, the receiving end voltage is outside the band since receiving end tap is maxed out. Fig. 13 shows the reactor tap positions during each step.

TABLE III
REACTOR AND UT OLTC TAP SUMMARY

Case A	Tap R	Tap S	UT OLTC	V_s	V_r	Current mode
START UP	23	17	1L	✓	✓	X
6 MINUTES	25	17	1L	✓	X	X
12 MINUTES	14	1	1R	X	X	✓
21 MINUTES	25	12	1L	✓	X	X

Fig. 14 and Fig. 15 shows the current and voltage over distance for no-load condition (after 30 minutes) and full-load condition (after 17 minutes).

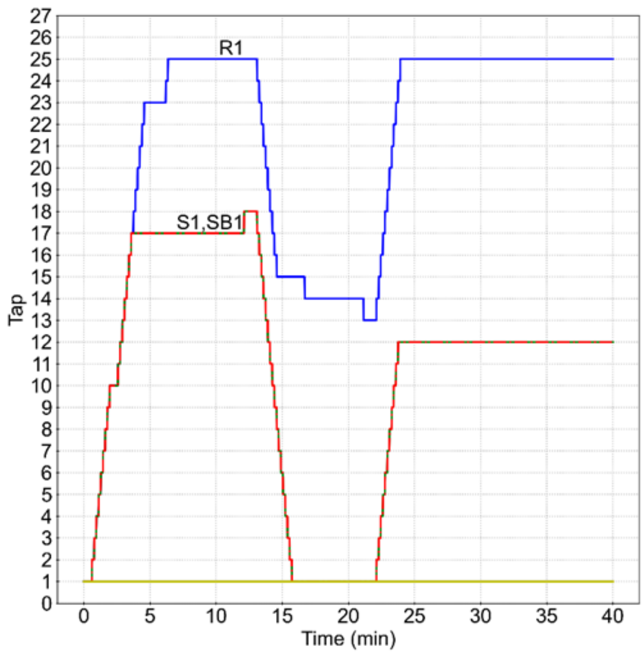

Fig. 13 Reactors Tap for Case A

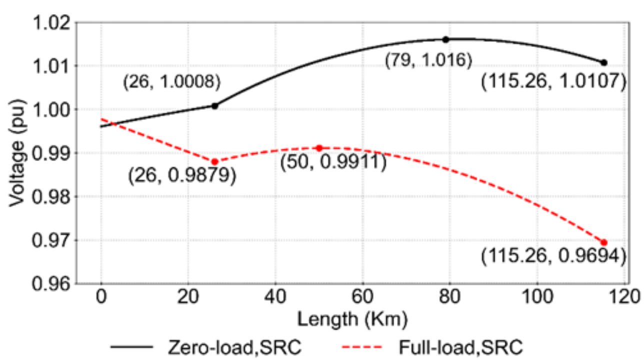

Fig. 14 Voltage Profile for Case A

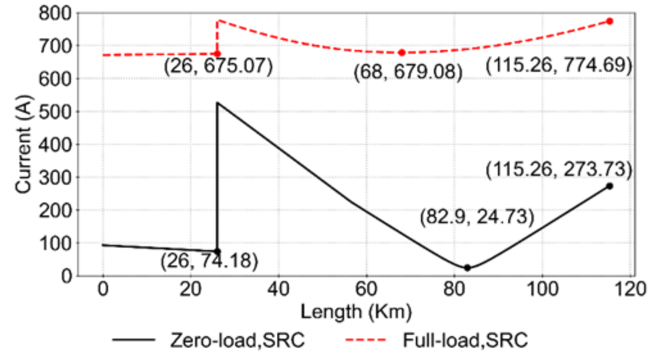

Fig. 15 Current Profile for Case A.

B. Energizing Double Submarine Cables at 380 kV

1. Start up the energization of first submarine cable. Receiving end breaker is still open.
2. After 6 minutes, Cable 1 receiving end breaker is closed with light load and offshore substation is energized.
3. After 12 minutes, the second submarine cable is energized. The receiving end breaker is still open. Equalizing of onshore and offshore tap position is executed.
4. After 18 minutes, Cable 2 receiving end breaker is closed. Equalizing of offshore tap position is executed.
5. After 24 minutes, the full load is added on onshore and offshore. SRC offshore is in voltage mode.
6. After 30 minutes loading is reduced to zero on onshore and offshore.

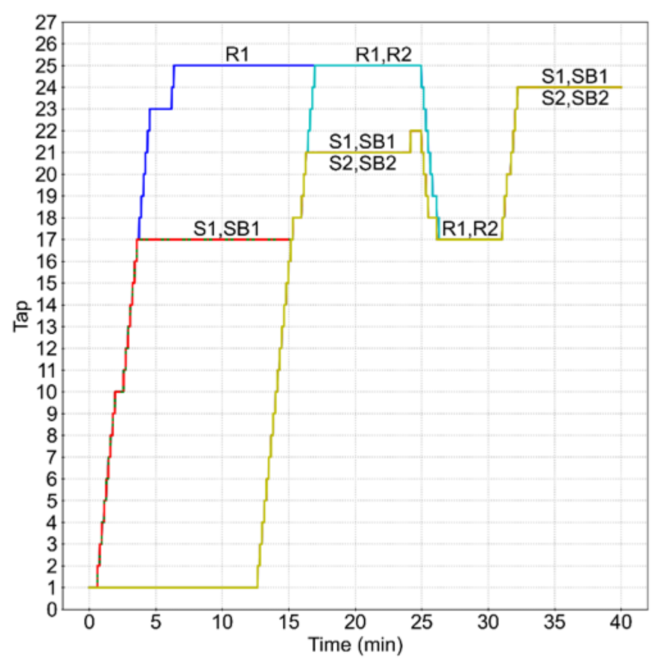

Fig. 16 Reactors Tap for Case B

Refer to Table IV and Fig. 16 for a summary of all tap positions and voltage and current satisfactions. Table IV shows that the offshore reactors cannot maintain voltage in the desired band ±0.01 at no load. The receiving end tap reaches maximum position. During all steps in Table IV SRC was in offshore voltage mode, not in current mode, since we have two cables energized.

TABLE IV
REACTOR AND UT OLTC TAP SUMMARY

Case B	Tap R	Tap S	UT OLTC	V_s	V_r
Start up	23	17	1L	✓	✓
6 minutes	25	17	1L	✓	x
12 minutes	25	21	1L	✓	x
18 minutes	25	21	1L	✓	✓
24 minutes	17	17	1R	✓	✓
30 minutes	24	24	1L	✓	✓

Fig. 17 and Fig. 18 shows the current and voltage over distance for no-load condition (after 30 minutes) and full-load condition (after 24 minutes).

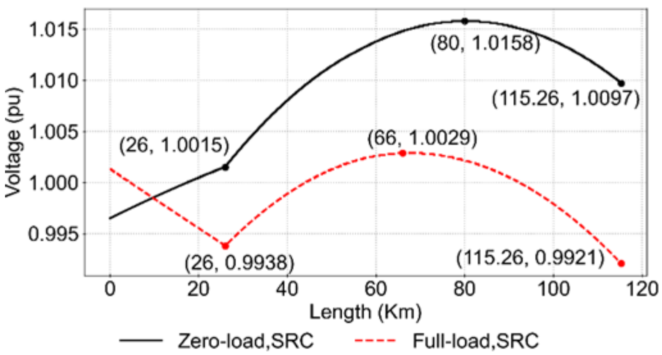

Fig. 17 Voltage Profile for Case B

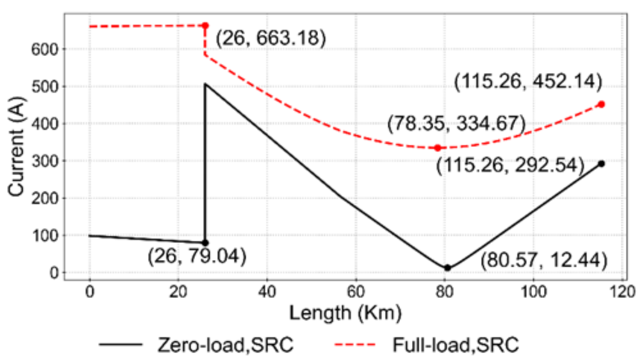

Fig. 18 Current Profile for Case B

C. *Energizing Double Submarine Cables at 392 kV*

1. Start up the energization of first submarine cable. The receiving end breaker is still open. The UT transformer OLTC is disabled. The UT voltage is adjusted so that the secondary transformer is at 1.035 pu.
2. After 6 minutes, Cable 1 receiving end breaker is closed with light load and offshore substation is energized. Hunting is detected.
3. After 12 minutes, the second submarine cable is energized. The receiving end breaker is still open.
4. After 18 minutes, Cable 2 receiving end breaker is closed and offshore cables are energized. Hunting is detected.
5. After 24 minutes, the full load is added on onshore and offshore. Hunting is detected.
6. After 30 minutes, loading is reduced to zero onshore and offshore. Hunting is detected.

TABLE V
REACTOR AND UT OLTC TAP SUMMARY

Case C	Tap R	Tap S	UT OLTC	V_s	V_r	Hunt
Start up	25	33	N	x	x	✓
6 minutes	25	33	N	x	x	✓
12 minutes	25	33	N	x	x	✓
18 minutes	25	33	N	x	x	✓
24 minutes	22	18	N	✓	✓	✓
30 minutes	25	33	N	x	x	✓

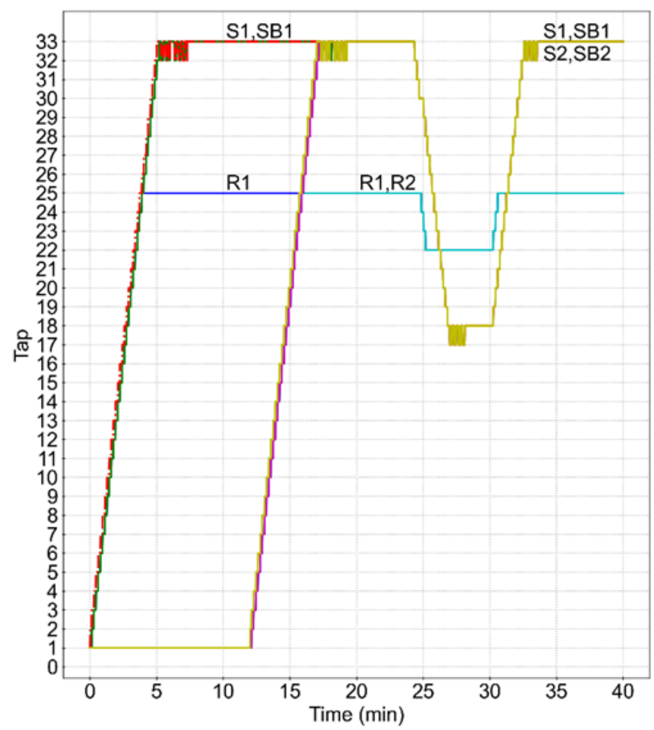

Fig. 19 Reactors Tap for Case C

Refer to Table V and Fig. 19 for summary of all tap positions and voltage and current satisfactions.

Table V shows that the onshore/offshore reactors cannot maintain the voltage in the desired band ±0.01 at no load. The receiving end tap reaches maximum position. During all steps in Table V hunting between voltage and reactive power objectives is detected on the sending side since it is not possible to satisfy both objectives with high voltage on UT side and with UT transformer OLTC not working.

Fig. 20 and Fig. 21 shows the current and voltage over distance for no-load condition (after 30 minutes) and full-load condition (after 24 minutes).

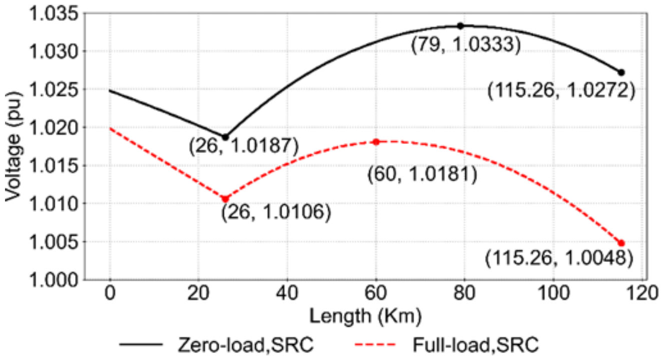

Fig. 20 Voltage Profile for Case C

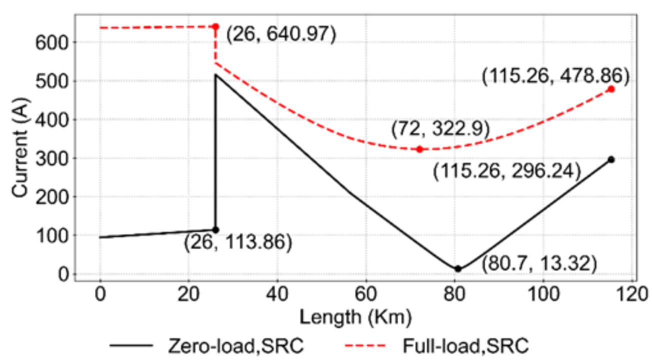

Fig. 21 Current Profile for Case C

D. Tripping One Submarine Cable Under the Full-Load Condition at 380 kV

1. Two submarine cables are energized as explained in section V. B.
2. After 24 minutes, the full load is added on onshore and offshore. Offshore is in voltage mode.
3. After 30 minutes, the second cable is tripped along with the bus reactor and system is at full load.
4. The offshore reactors tap up to bring the current in band SRC controls the offshore reactor to bring the current in band and then stops control.

Refer to Table VI and Fig. 22 for summary of all tap positions and voltage and current satisfactions. Table VI shows that the offshore voltage cannot be maintained in the desired band +/– 0.01 at full load because SRC is in current control mode

TABLE VI
REACTOR AND UT OLTC TAP SUMMARY

Case D	Tap R	Tap S	UT OLTC	V_s	V_r	Current Band
24 minutes	17	17	1R	✓	✓	x
30 minutes	15	1	1R	x	x	✓

Fig. 23 and Fig. 24 shows the current and voltage over distance for a full-load condition with two cables (after 24 minutes) and with one cable (after 30 minutes).

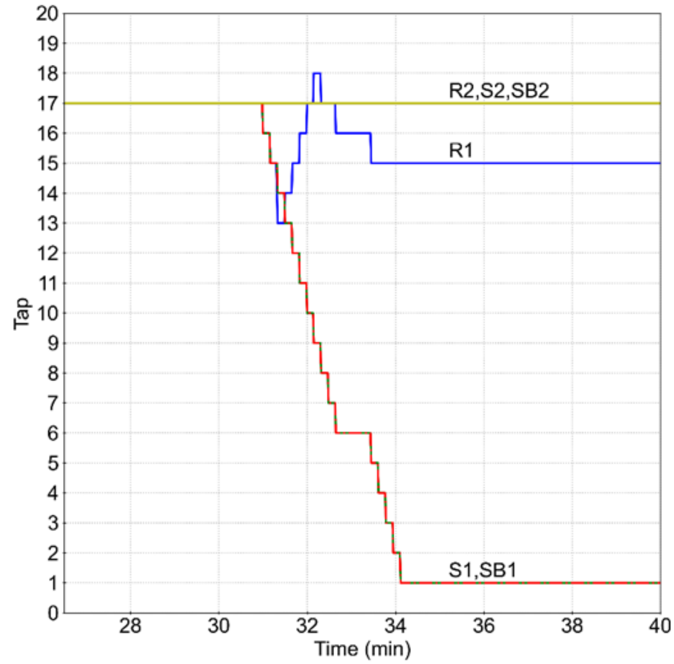

Fig. 22 Reactors Tap for Case D

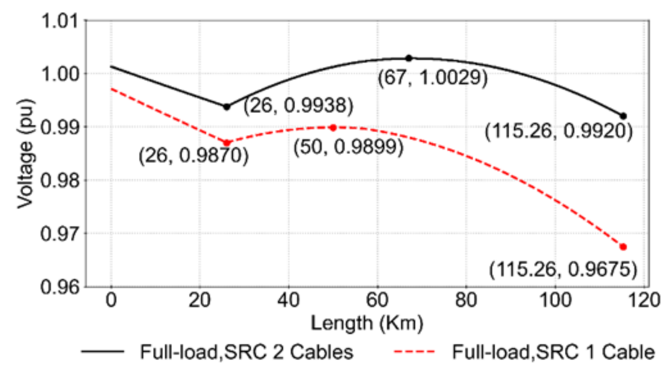

Fig. 23 Voltage Profile for Case D

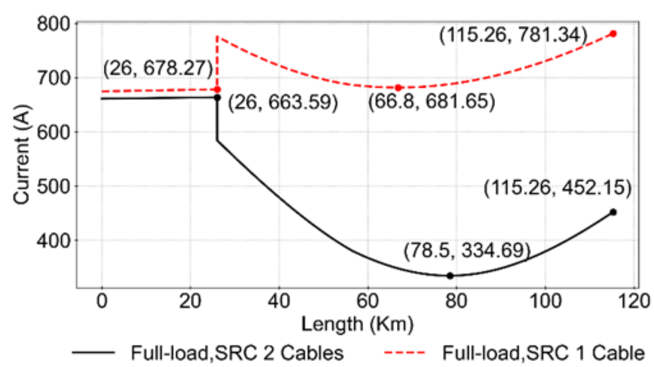

Fig. 24 Current Profile For Case D

VII. CONCLUSIONS

This paper presents a shunt reactor control (SRC) algorithm to control submarine cables shunt reactors compensation. SRC objective is to control bus voltage onshore/offshore, utility power factor, and submarine cable current. Detail flowchart of SRC algorithm is introduced and explained. Fundamental equations for long transmission line and submarine cable are highlighted in the paper. Energizing the submarine cables without shunt reactor and with full shunt reactor is explained. The paper also presents a PLS. PLS is designed to shed loads onshore/offshore if the current exceeds the ampacity of OHTL/submarine cable to protect these important power system components. Hardware-in-loop (HIL) simulation shows that SRC can achieve its goals by maintaining the voltage, current and power factor within the designed agreed tolerance throughout the energization and de-energization with maximum and minimum loading.

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X. VITAE

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