On the Short Circuit Current Contribution of HVDC Light

Y. Jiang-Häfner, M. Hyttinen, and B. Pääjärvi

Abstract—**Voltage Source Converter (VSC) based HVDC transmission systems are available in market for power rated between a few MVA to a few 100s of MVA. The new system results in many application opportunities, and new applications in turn bring up new issues of concern. This paper presents a comprehensive investigation on one of the concerned issues, which is the contribution of HVDC Light to short circuit currents. Different AC network conditions, load conditions and fault types are considered under different operation conditions and control modes. Results from simulations with complete control functions as in real systems are presented and discussed. The associated control and protection strategy is also discussed. Finally, a comparison is provided between the HVDC Light and conventional HVDC, the SVC and the STATCOM regarding the impact on the short circuit current.**

Index Terms-- HVDC, VSC, transmission, short circuit current, AC fault

I. INTRODUCTION

HVDC Light is the newly developed HVDC transmission technology, which is based on extruded DC cables and voltage source converters consisting of Insulated Gate Bipolar Transistors (IGBT's) with high switching frequency. Under more strict environmental and economical constraints due to the deregulation, the HVDC Light provides the most promising solution to power transmission and distribution [1, 2, 3, 4], thanks to its unique features:

- Active and reactive power exchange can be controlled flexibly and independently.
- The power quality and system stability can be improved via continuously adjustable reactive power support with AC voltage feedback control.
- Feed AC systems with low short circuit power or even passive networks with no local power generation.

The good operation experiences with several commercial installations [5, 6, 7] in last three years show that the HVDC Light technology is mature, and it has attracted a lot of new customers in the competitive market. One of the most concerned issues from customers is the contribution of HVDC Light to short circuit currents. The main reason for being interested in this issue is that the contribution of the HVDC Light to short circuit currents may have some significant impact on the ratings for the circuit breakers in the existing AC systems.

This paper presents the result after a comprehensive investigation on the issue regarding the contribution of HVDC Light to short circuit currents. Both the theoretical analyses and practical simulations with complete control functions have been performed. The paper will first give a brief description about the HVDC Light transmission system and its terminal control functions. Following that the main results will be presented and discussed. Different AC network conditions, load conditions and fault types will be considered under different operation conditions and control modes. The associated control and protection strategy will also be discussed. The paper will compare and discuss the short circuit impact from the HVDC Light versus the conventional HVDC, the SVC and the STATCOM as well.

II. HVDC LIGHT TRANSMISSION SYSTEM

The HVDC Light transmission system mainly consists of two cables and two converter stations. Each converter station is composed of a voltage source converter (VSC) built up with IGBTs, phase reactors, ac filters and transformer, as shown in Fig. 1. By using pulse width modulation (PWM), the amplitude and phase angle (even the frequency) of the converter AC output voltage can be adjusted simultaneously. Since the AC side voltage holds two degrees of control freedom, independent active and reactive power control can be realized.

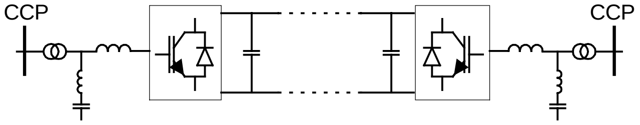

Fig. 1. HVDC Light transmission system.

Regarding the active power control, the feedback control loop can be formulized such that either tracks the predetermined active power order, or tracks the given DC voltage reference. This gives two different control modes, i.e., active power control mode (Pctrl) and DC voltage control mode (Udcctrl). If one station is selected to control the power, namely, in Pctrl mode, the other station should set to control the DC voltage, namely, in Udcctrl mode.

Regarding the reactive power control, the feedback control loop can be formulized such that it either tracks the predetermined reactive power order, or tracks the given AC voltage reference. This also gives two control modes, i.e.,

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The authors are currently working for ABB Utilities AB, Power Systems in Sweden.

reactive power control mode (Qctrl) and AC voltage control mode (Uacctrl). The two control modes can be chosen freely as desired in each station.

Under the normal operation condition, the VSC can be seen as a voltage source. However, under abnormal operation conditions, for instance, during an ac short-circuit fault, the VSC may be seen as a current source, as the current capacity of the VSC is limited and controllable.

III. INVESTIGATION OF SHORT-CIRCUIT CURRENT

A. Studied AC System

The studied AC system has a mixture structure in radial and mesh connection, as shown in Fig. 2. It includes high, medium and low voltage buses. The AC transmission lines are modeled with π-link. The loads are constant current loads.

Three types of fault, namely, the close-in fault; the near-by fault and the distant fault, are applied at bus A, B and C, respectively. A 3-ph close-in fault results in a voltage reduction of almost 100%, whereas a 3-ph near-by fault and distant fault result in voltage reduction on CCP bus of about 80% and 20%, respectively.

In the following discussion, the short circuit ratio (SCR) is defined as the short circuit capacity of the AC system observed at CCP divided with the power rating of the converter.

B. The Impact of Strength of AC Networks

The possible maximum relative short circuit current increment (ΔImax) is determined by the short circuit ratio (SCR). Supposing that the ΔImax is defined as (1), it is found that the ΔImax is inversely in proportional to the SCR as the solid curve shown in Fig. 3.

$$\Delta I_{max} = \frac{I_{SC\_HVDC\_L} - I_{SC}}{I_{SC}} \tag{1}$$

where, I_{SC} is the short-circuit current of the original AC system alone at a 3-ph fault and $I_{SC\_HVDC\_L}$ is the short-circuit current of the AC system with converter station connected and in operation at the same fault.

It should be noticed that the solid curve in Fig. 3 is valid if there is no tap-changer, or the tap-change is at the position corresponding to the nominal winding ratio. If there is a tap-changer in transformer, the AC network will observe a different current although the maximum current of the converter is a fixed value. Therefore, the maximum possible short circuit current increment is in the boundary defined by the two dashed curves. AC networks with SCR equal to 1.85, 3.14 and 12 have been simulated and the results are also shown in figure 3 with black dots.

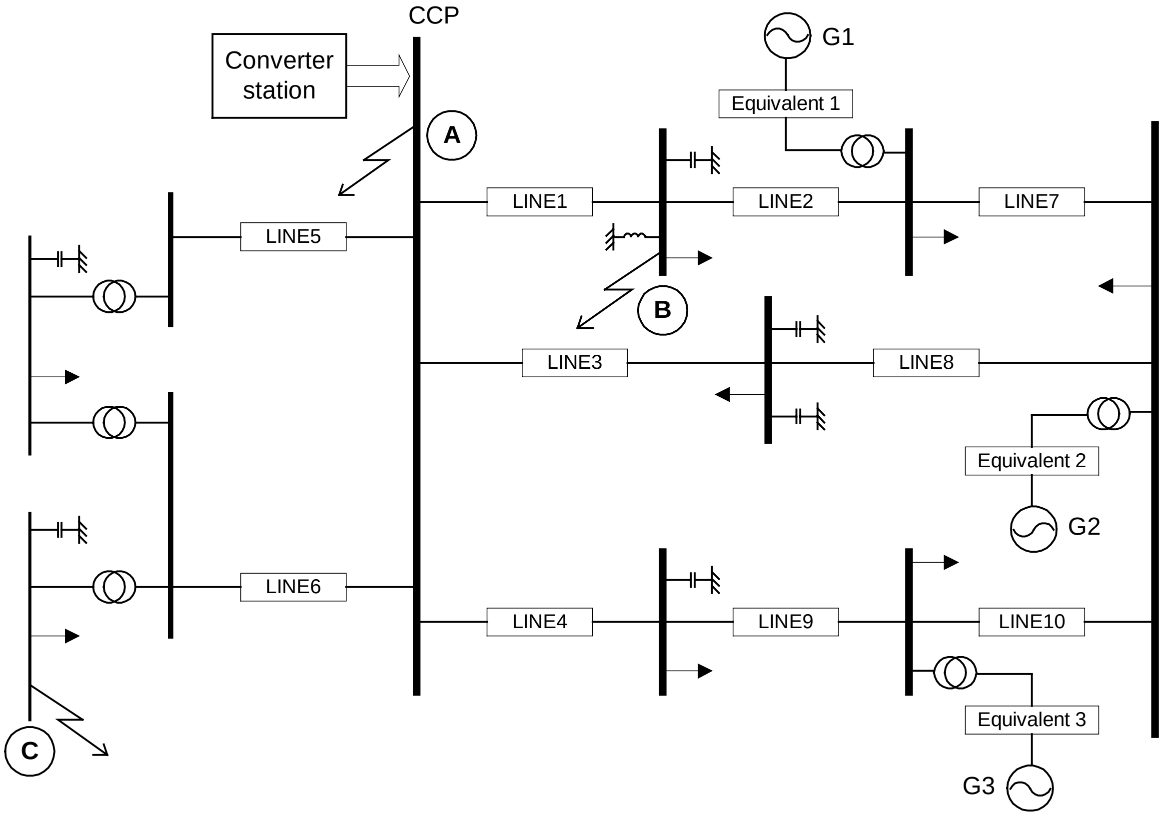

Fig. 2. Studied AC system in single-line diagram.

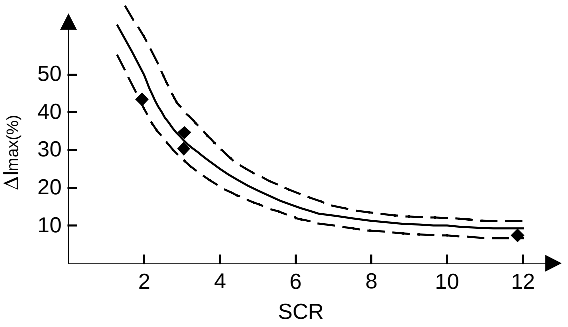

Fig. 3. Characteristic showing the impact of AC network strength.

Different control modes and different operation points may change the short circuit current contribution from the VSC. However, it will not be higher than the ΔI_{max}. For instance, the short circuit current contribution from the VSC will not exceed 12% if the SCR is 10 and voltage tap-change range is ± 20%.

C. *The Impact of Control Modes*

The current is mainly limited by the impedances of transmission lines and transformers when a short circuit occurs. Since the impedance of lines and transformers is dominated by the inductive impedance, the short circuit current is mainly consisted of reactive current. Because of that, the choice of different control modes in respect of the active power control does not give any impact to the short circuit current. Therefore, the following discussion will focus on the choice between the control modes Qctrl and Uacctrl.

It is important to notice that the change of short circuit current and the variation of bus voltages usually go hand in hand. The increase of short circuit current, namely, the increase of short circuit capacity, will improve the voltage stability and minimize the reduction of bus voltage due to faults. Inversely, the reduction of short circuit current may leads to voltage instability and voltage collapse during faults, in particular in weak AC systems. With Uacctrl control mode, the reactive current generation will be automatically increased when the AC voltage decreases. Therefore, the Uacctrl control mode provides the possibility of improving the voltage stability and minimizing the reduction of bus voltage due to faults. On contrast, with Qctrl control mode it has the potential risk of getting voltage instability or voltage collapse during faults if the AC system is weak and no control protection action is taken. One way to avoid this potential risk is that the control is automatically switched to Uacctrl if the AC voltage is detected out of the specified range (Umin~Umax, for instance, 0.9~1.1 per-unit). The other way is that the maximum value for the current order should be decreased with the AC voltage decreasing during faults. If the current from the VSC is reduced, its contribution to the short circuit current will also be reduced. Therefore, with Qctrl control mode the contribution of VSCs to the short circuit current is almost neglectable independent of operation points, or load level. It will then be only interesting to discuss the Uacctrl control mode in respect of different operation points.

D. *The Impact of Operation Points*

As it has been discussed, the maximum possible short circuit increment (ΔImax) due to HVDC Light is determined by the SCR. It will occur if the VSC is operating at zero active power, namely, it is operating as an SVC or STATCOM. Fig. 4 shows the characteristic of short circuit current contribution versus the load level. The two dashed curves are the result by taking into account the transformer winding ratio variation due to the tap-changer.

AC networks with SCR equal to 3.14 has been simulated. For different load levels the observed short circuit currents, during a 3-ph close fault, are marked with black dots in Fig. 4.

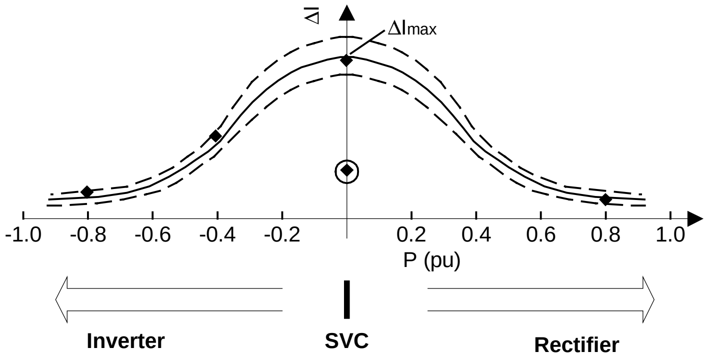

Fig. 4. Characteristic showing the impact of load levels.

It should be noted that the short circuit current would be also reduced if the current order is also limited with the Uacctrl. The black dot with a circle in Fig. 4 shows the result when the current order is limited to 35% of the rated current during the AC fault.

E. *The Impact of Fault Type and Location*

If the fault current is evaluated in per unit with the base value equal to the 3-ph fault current at the corresponding fault location and without HVDC Light connected, it turns out that the impact of the fault location seems to be insignificant.

Under the same load and operation condition, the 1-ph fault current is usually smaller than the 3-ph fault current. This is because the average voltage reduction is smaller for 1-ph fault, thereby the required reactive power generation is smaller during a 1-ph fault. In addition, the VSC only generates balanced 3-phase currents, even if the AC bus voltage is unbalanced due to 1-ph faults.

As an example, Fig. 5 shows 1-ph and 3-ph fault currents at different locations (bus B and bus C in Fig. 2) under the same operation condition (SCR=3.14, P=-0.8 and Uacctrl). Currents in plot (a) and (b) have one base value, and currents in plot (c) and (d) have another base value. Plot (b) shows that the peak value is slightly higher than 1, which means the short circuit current with HVDC Light is slightly higher than that without the HVDC Light for the same fault.

It should be noticed that when a close-in short-circuit fault occurs the connected converter station will only feed the fault current. This implies that the current during the fault in the rest AC lines will be the same as the original AC network alone. In other words, the close-in fault isolates the HVDC Light terminal from the AC network. If it is the circuit breakers in the AC network to be mainly concerned, this type of fault will be less significant. This is why that the performed studies do not focus on this type of faults.

F. The Impact of Control and Protection

Different control strategies may result in different short circuit currents for the same fault. Fig. 6 shows three cases:

- Case 1: with AC voltage control and the maximum current order is kept as the rated value during the fault.
- Case 2: with AC voltage control and the maximum current order depending on the AC voltage is reduced to 0.35 pu during the fault.
- Case 3: with reactive power control and the maximum current order depending on the AC voltage is reduced to 0.35 pu during the fault.

Case 1 gives the highest short circuit current contribution, whereas Case 3 gives the lowest contribution. The reason for a lower contribution in Case 3 than in Case 2 is that the Q order was set to - 0.24 (absorption) before the fault and that it keeps absorbing reactive current even during the fault.

It is important to observe from Fig. 6 that the higher the fault current, the higher the bus voltage. The higher fault current may have some negative impact to the circuit breakers. However, the resulted higher bus voltage during the fault may have a positive impact to the voltage and power stability of the AC network, and the connected electricity consumers may suffer less from the disturbance.

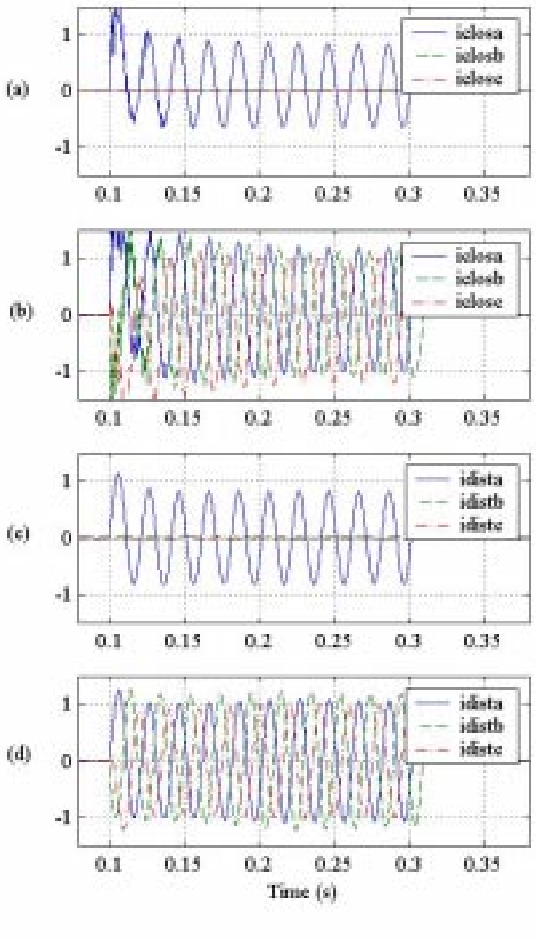

Fig. 5. Different fault currents in per unit of the corresponding 3-ph fault current without HVDC Light.
(a): 1-ph close fault current.
(b): 3-ph close fault current.
(c): 1-ph distant fault current.
(d): 3-ph distant fault current.

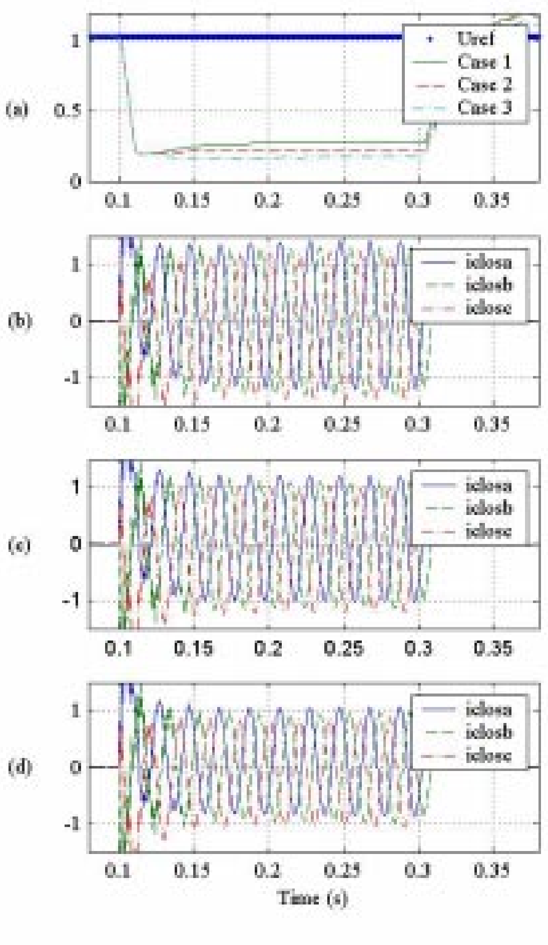

Fig. 6. AC voltage and fault current with different control strategies.
(a): AC voltage measured at CCP (see Fig. 2.).
(b): Case 1 – with Uacctrl and no change on current order limit.
(c): Case 2 – with Uacctrl and current order limit depending on voltag.
(d): Case 3 – with Qctrl and current order limit depending on voltage.

G. *Line Current During Faults*

The proceeding discussion has been mainly focused on the short-circuit current at faults. What is really concerned is actually the line current, as the circuit breakers are usually installed at the ends of lines. Therefore, it is more interesting to know the impact of HVDC Light on the current in different lines near by a fault. Currents measured in LINE1, LINE2, LINE3, LINE4 and LINE5 are illustrated in Fig. 7 during a 3-ph fault occurred at bus bar B (seen Fig. 2). Curves corresponding to “with vsc” are resulted from Case 1 (see Fig. 6). It can be seen from the figure that the contribution of HVDC Light results in a significant impact only on the current of LINE1, which is in the shortest electric path from the converter station to the fault. It is interesting to notice that the fault current in LINE3 and LINE4 is slightly reduced and the load current in LINE5 is slightly increased compared with no HVDC Light connected. From this example, it is seen that the contribution from the HVDC Light makes the difference between the current of health lines and faulted lines larger, which may have a positive impact in distinguishing the faulted and health line.

When a short circuit occur in the AC network, the sudden AC bus voltage variation may result in overcurrent to the converter due to the measurement and control delay. As soon as the overcurrent in the converter is detected, the protection will trigger a temporary blocking of converter. This scenery is illustrated in Fig. 7 with Isvc. It is obvious that the transient and steady state current contribution from the HVDC Light is different. Nevertheless, it should be noted that usually the circuit breakers do not react to the overcurrent spontaneously, and it often has a delay time of about 60 ~100 ms. Therefore, it is the steady state current during the fault that should be considered.

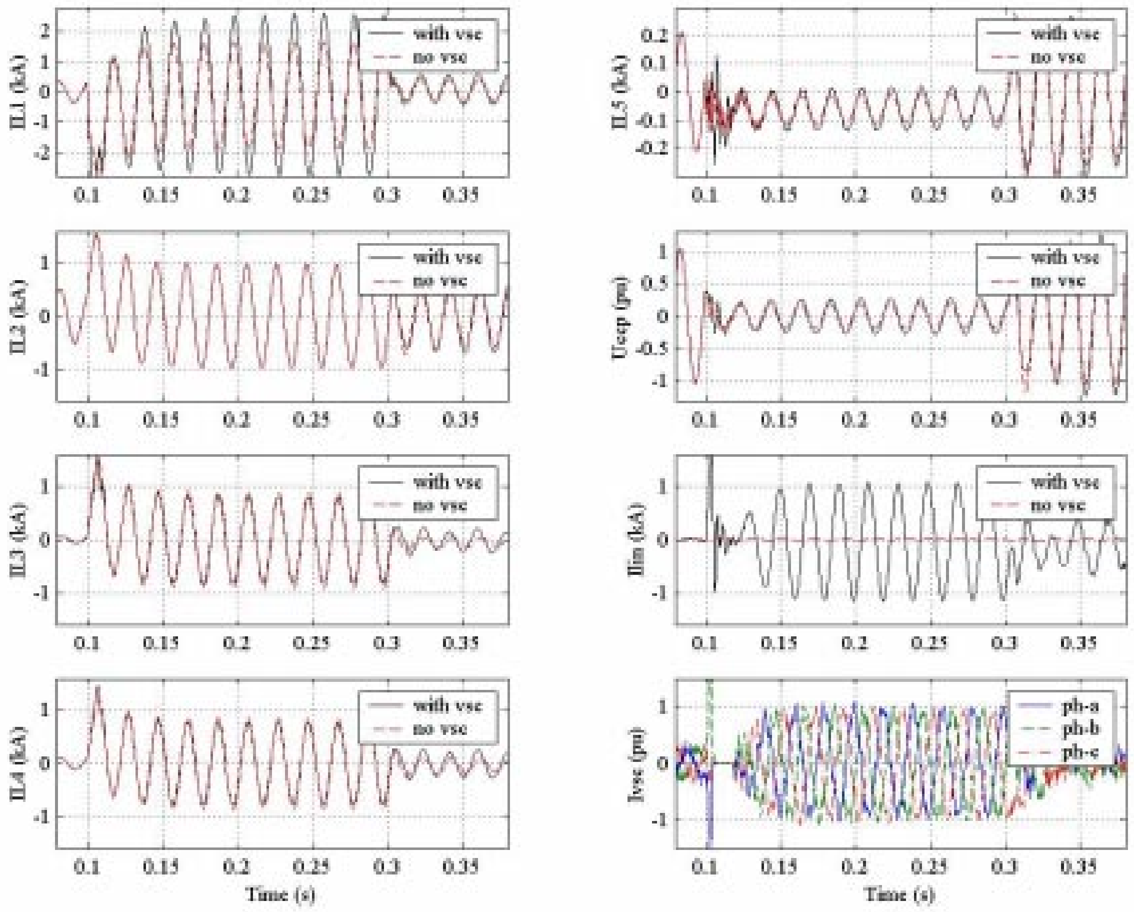

Fig. 7. Currents during a 3-ph close fault. (a): IL1 - current in LINE1for phase A; (b): IL2 - current in LINE2 for phase A; (c): IL3 – current in LINE3 for phase A; (d): IL4 – current in LINE4 for phase A; (e): IL5 – current in LINE5 for phase A; (f): Uccp – voltage at CCP for phase A; (g): Ilin – current in primary side of converter transformer for phase A; (h): Ivsc – current in phase reactors for phase A, B and C.

IV. COMPARISON BETWEEN HVDC LIGHT AND OTHER EXISTING HIGH POWER ELECTRONIC APPARATUS

A. Conventional HVDC

In the conventional HVDC, there is a well-known function in the control, that is, Voltage Dependent Current Order Limiter (VDCOL). The main purpose for VDCOL is to avoid voltage and power instability during and after faults in AC networks. Due to VDCOL, the current order will be reduced when the AC voltage is reduced due to AC faults. In addition, the converter made of thyristors in conventional HVDC can not supply any reactive power for the AC network. Therefore, the conventional HVDC in principle does not contribute any short-circuit current. The HVDC Light may contribute short-circuit current depending on control modes, operation points and control strategies.

B. SVC

The conventional SVC usually consists of Thyristor Switched Capacitors (TSCs) and/or Thyristor Controlled Reactors (TCRs). From control point of view, it can be seen as controllable impedances. Therefore, its current capability depends naturally on the AC voltage. The closer the AC fault, which gives the lower AC voltage at SVC bus, the lower the current will be supplied from the SVC. However, the current capability of a converter in HVDC Light does not depend naturally on the AC voltage. It is possible to supply fully current at very low AC voltage, and it is also possible to make it supply current depending on the AC voltage.

C. STATCOM

The Static Var Compensator (STATCOM), liking HVDC Light, is also composed of VSC. When the HVDC Light does not transmit any active power, each of its terminal stations functions identical as an STATCOM. As it has been discussed, the maximum possible short circuit contribution for HVDC Light occurs when the VSC is operating at zero active power, namely, it is operating as an STATCOM. Therefore, Both the STATCOM and HVDC Light will have the same short circuit current contribution, if the same control and protection strategy is adopted.

V. CONCLUSION

A comprehensive investigation on the issue regarding the contribution of HVDC Light to short circuit current has been performed. The studies lead to the following conclusions. The HVDC Light, in contrast to the conventional HVDC which does not contribute any short circuit current, may contribute some short circuit current. The possible maximum short circuit current contribution is determined by the SCR. It is inversely in proportional to the SCR and it occurs when the transmission system is operating at zero active power. Hence, it is comparable to the STATCOM as long as the maximum short circuit current contribution is concerned.

The amount of contribution depends on control modes, operation points and control strategies. With the reactive power control mode, the short circuit current contribution will be limited due to the current order limit decreasing with the voltage. With the AC voltage control mode, the short circuit current contribution will be increased with the decreasing of active power, if the current order limit is not changed. If the current order limit is decreasing with voltage, the short circuit current contribution will be small even if the load level is low.

The contribution to the short circuit current is irrelevant to the fault location if the fault current is evaluated in per unit with the base value equal to the 3-ph fault current at the corresponding fault location and without HVDC Light connected. Under the same load and operation condition, the 1-ph fault current is usually smaller than the 3-ph fault current.

Finally, it should be noticed that in associated with higher short-circuit current the voltage stability and performance is likely to be improved. If the HVDC Light contributes a higher short-circuit current, the voltage dip due to distant fault is possibly reduced and thereby the connected electricity consumers may suffer less from disturbances.

VI. REFERENCES

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VII. BIOGRAPHIES

Ying Jiang-Häfner received her B. Sc. And M. Sc. Degrees in electrical engineering from Huazhong University of Science and Technology, China, respectively in 1984 and 1987. She received Ph. D. Degree in electrical engineering from Royal Institute of Technology (KTH) of Sweden in 1998.

She was a Teaching Assistant at Huaihai University in China from 1987 to 1991, and a Research Assistant in KTH from 1991 to 1997. Since 1998 she joined the System Development Department of ABB Power System in Sweden. During the time in KTH she had been one of the principal researchers in ABB-EPRI(USA)-Vattenfall jointed research project “Evaluation of Performance of Static Condensers” and ABB-Vattenfall-Elforsk jointed research project “Evaluation of Performance of UPFC”. She has been involved in the design and development of control system for HVDC Light since she joined ABB.

Mats Hyttinen was born in Kungsbacka, Sweden on December 11 1958. He graduated from Chalmers University of Technology in Gothenburg, Sweden, 1982 with a master of Science degree in electrical engineering.

In 1982 he joined the HVDC Design Department of ASEA where he has been working with design and development of HVDC and HVDC Light systems. The work includes power system aspects as well as control and protection systems. (ABB Utilities AB, Power Systems, Lyviksvägen 3 77180 Ludvika Phone: +46240782207 Fax: +46240782177 email: mats.hyttinen@se.abb.com)

Bo Pääjärvi, was born in Pajala, Sweden, on 7 December, 1949. He studied at Chalmers University of Technology, where he achieved Masters Degree in Electrical Engineering in 1974. His employment experience includes 23 years in the field of HVDC Engineering and Project Management in ABB and 5 years in railway engineering at the Swedish State Railways. Bo Pääjärvi is currently keeping the position as Vice President at ABB Utilities AB, Power Systems, in Ludvika, Sweden.