Solving Zero-Miss with Cable Energisation at Voltage Peak, Based on Insulationcoordination Study Results

Unnur Stella Gudmundsdottir and Per B. Holst

***Abstract*—Zero-Miss can be a problem, when a long HV/EHV cable is directly compensated for more than 50% of the cables reactive power. For minimizing switching transient overvoltages, a cable system is very often, without further due, energised during zero voltage. This causes a DC offset in the shunt reactor current and therefore a DC current in the line breaker, with delayed zero crossing.**

The present paper covers an analysis of the zero-miss problem, where an insulation co-ordination study is used for finding a technically optimal and cost effective solution. Synchronized switching at voltage peak is proposed, and no unacceptable overvoltages are identified in the analysis.

***Keywords*: Zero-miss, insulation co-ordination, Underground Cable, reactive compensation**

I. Introduction

LONG or many HV and EHV cable lines require directly connected shunt compensation, for keeping the network voltage within operational limits during energization. Academic studies have revealed the possibility of a zero-miss problem, when switching with such a cable system, [1], [2], [3]. The existence of this problem has later been validated with field measurements, on a 21.5 km 132 kV cable line for an offshore wind farm in Denmark.

A DC offset due to the shunt reactor can take several sec. to damp, in which time the line breaker cannot be re-opened. An actual example, for a line breaker on the 400 kV Lillebælt cable line in Denmark, is shown in Fig. 1.

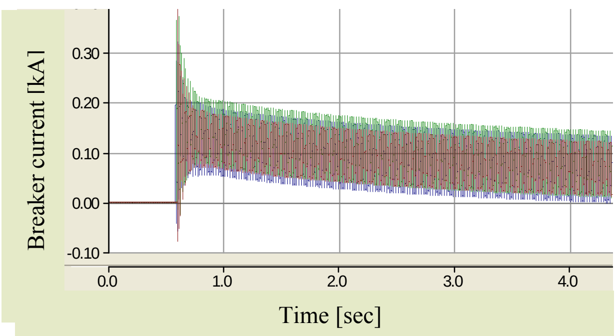

Fig. 1 Line breaker current during energization of a 80% compensated 400 kV cable line. The breaker cannot be re-opened until 4.5 sec after cable energization.

U. S. Gudmundsdottir is a Cable Specialist and Group Leader in the Transmission Department at Energinet.dk, 7000 Fredericia, Denmark (e-mail: usg@energinet.dk).

P. B. Holst is a project manager in Grid Planning at Energinet.dk, 7000 Fredericia, Denmark (e-mail: pht@energinet.dk).

Paper submitted to the International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada July 18-20, 2013.

It is important to note here, that a zero-miss phenomena is not problematic in itself. The hazard of having zero-miss phenomena lies in the possibility of energising a faulted cable line. This is due to the fact, that if a circuit breaker is closed on a faulted cable line, with zero-miss phenomena, the circuit breaker cannot be re-opened before zero crossing appears which may in many cases take several seconds.

Several countermeasures have been proposed for a cable line with a directly connected shunt reactor [4]. Not all of these have been used in practice, and few have been thoroughly tested. One of the proposed countermeasures is using point on wave synchronized switching, where the cable line, with reactor, is energised at voltage peak. This solution has however often been theoretically excluded due to risk of high transient overvoltages [2], without actual studies being performed.

In this paper, two non-related 400 kV cable lines in Denmark are used as case studies, for demonstrating the usage of the countermeasure of synchronized energization. One case is a single double system, with 2 cables per phase, while the other case has two parallel double systems, or 12 cables in total. Both systems have been modelled using the EMT software EMTDC/PSCAD, and a thorough insulation co-ordination study has been performed.

II. Zero-miss countermeasures

Several countermeasures have been proposed, for solving the zero-miss phenomena during energization of a >50% compensated cable line, with a directly connected shunt reactor.

A. Sequential switching

Sequential switching has been proposed and used in several cases [5]. The disadvantage of this countermeasure, is that in case of protection scheme or breaker failure, the zero-miss problem is moved to the next set of breakers. Furthermore the solution requires circuit breakers for the directly connected shunt reactor.

B. Opening of faulted phase

Delayed opening of healthy phases has been proposed as a possible countermeasure. By doing this, there is a risk of ferroresonance, as this will cause asymmetry of a none or lightly loaded cable with one phase open and two phases connected.

C. Pre-insertion resistor

Breaker with pre-insertion resistor is a solution, which can remove the zero-miss phenomena. This type of breaker is however not available for GIS stations, and has up to date not been used for EHV air breakers. Equipment for this solution is therefore not available or very expensive.

D. Additional series resistance

Additional series resistance in shunt reactor for energization is a countermeasure that requires special control to bypass the series resistance after energization. Furthermore, this resistance must be thermally designed for the shunt reactor current, during switching of each phase.

E. Delayed reactor switching

Delayed reactor switching has been proposed as the current of a non-compensated cable does not have any DC component. However, energising the shunt reactor after the cable is not always possible on HV and EHV cable systems, as in many cases the reactor shall be energised with the cable, for keeping the network voltage within operational limits during energization.

F. Variable reactor

Using a variable reactor, where the reactance is lowered during switching has been used in Denmark. This however requires expensive shunt reactors, as well as there is a high risk of too high voltage disturbances, as the network voltage might exceed operational limits during energization.

G. Star point resistance

Shunt reactor star point series resistance is a countermeasure that damps the DC component in the reactor during energisation. This solution requires a series resistance of electrical size precisely calculated and designed for effective damping, and with thermal design for the possible current in the star point.

H. Synchronized voltage peak switching

Synchronized point on wave switching in busbar peak voltage is a countermeasure that has long been criticised due to risk of large transient overvoltages. Furthermore, energization at voltage peak can overstress the top winding insulation of the shunt reactor, due to the nonlinear extra transient dI/dt. Due to this, the top winding of the shunt reactors most often include extra insulation. This countermeasure has very low cost. For using the method a single-phase circuit breaker is required, as well as a control software ensuring synchronised switching. Furthermore, an insulation coordination study must be performed, studying the size of the overvoltages during energization, and the breaker current. As this solution has been criticized only based on possible risk of large transient overvoltages, and as this is the effectively cheapest solution with high effect, synchronized point on wave switching is chosen for further studies in this paper.

III. Cable Energization at Voltage Peak

A directly compensated cable line is a shunt connection of inductance and capacitance as shown in Fig. 2. This can cause the zero-miss phenomena, as the current in the line breaker is the sum of the inductive and capacitive current. The AC part will be zero for a 100% compensated line.

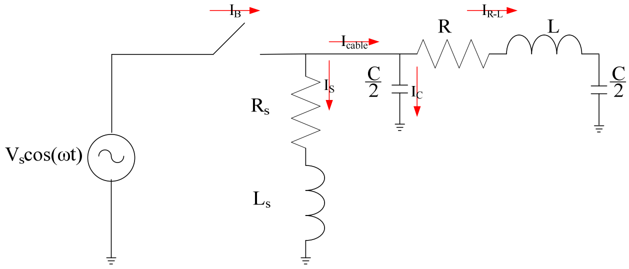

Fig. 2 Single line diagram of the shunt reactor and cable (represented by a single PI).

A. Breaker current

The current of the shunt reactor depends on the moment of energization, as shown in (1).

$$V_S\cos(\omega t) = R_S I_S + L_S\frac{dI_S}{dt}$$
$$\Rightarrow I_S = \frac{V_S}{L_S}\int\cos(\omega t)dt - \frac{R_S}{L_S}\int I_S dt = \frac{V_S}{L_S}\cdot\frac{\sin(\omega t)}{\omega} - \frac{R_S}{L_S}\int I_S dt \quad (1)$$

Where $V_s cos(\omega t)$ is the voltage across the shunt reactor, L_s is the inductance of the shunt reactor, R_s is the loss resistance of the shunt reactor and I_s is the current through the shunt reactor.

If $V_s cos(\omega t)$ is zero at the moment of energization, then I_s can be calculated using (2).

$$I_S = I_{S0}e^{-\frac{R_S}{L_S}t} \quad (2)$$

Where the DC component is damped with the time constant $\tau = L_S / R_S$

If $V_s$cos(ωt) however, is at voltage peak at the moment of energization, then I_s can be calculated using (3), and there is no DC component in the shunt current.

$$I_S = \frac{V_S}{\sqrt{R_S^2 + (\omega L_S)^2}}\cos\left(\omega t - \tan^{-1}\left(\frac{\omega L_S}{R_S}\right)\right) \quad (3)$$

The moment of energization is therefore essential when studying zero-miss phenomena and connection during synchronized voltage peak will remove the phenomena all together. It is though important to note, that actual circuit breakers have mechanical delay of up to ±1.5 ms.

In order to remove zero-miss for energization at voltage maximum ±1.5 ms, the sum of the cable, and shunt reactor current must cross zero. Theoretically, for energization precisely at voltage maximum, 100% compensation of the cable line is possible, but due to the mechanical delay of the circuit breaker, there is a theoretical maximum to how large the compensation can be, for ensuring no zero-miss. This degree is given in (4).

$$\%_{compensation} = 100 \cdot \frac{\sin(2\pi ft + n)}{\sin(2\pi ft + n) - \sin(t_0)} \quad (4)$$

Where f is the network frequency, $t_0 = 2\pi \frac{t_{delay}}{1/f}$, $n = \frac{3\pi}{2}$. For a mechanical delay of 1.5 ms, and frequency of 50 Hz, the maximum theoretical compensation is 69%, calculated by (4) where t=0 is the time of breaker closing. Due to the resistance in the system, this is normally higher, often around 75%. Fig. 3 shows the cable and shunt reactor AC current difference for various degrees of compensation, with mechanical delay of 1.5 ms and system frequency of 50Hz.

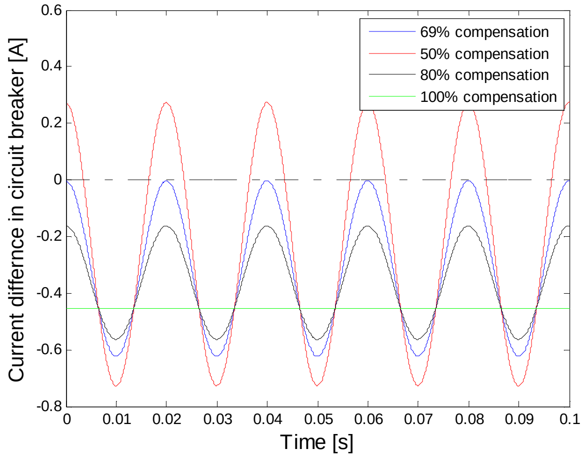

Fig. 3 Breaker current for energization in voltage maximum +1.5 ms, for different levels of compensation.

B. *Overvoltages*

When energizing during voltage peak, a travelling wave with full amplitude is excited. This travelling wave will be reflected and refracted at every change in the line impedance, both at transitions for transmission lines made of an Overhead Line (OHL) and an Underground Cable (UGC), and for each joint of a UGC due to the 6 different modes created [6]. This can be explained by the different travelling wave velocity, which depends on the line propagation constant γ (5).

$$\gamma = \sqrt{[Z][Y]} = \alpha + j\beta = \alpha + j\frac{\omega}{v} \quad (5)$$

Where Z and Y are the line impedance and admittance respectively, ω is the angular velocity, α is the propagation attenuation and v is the propagation velocity.

Due to change in the propagation constant, the travelling velocities, for different modes and for different line segments of the energized line, will be different and a ladder effect will cause building up of the voltage. As the travelling wave is excited with full amplitude, the ladder effect will cause transient overvoltages. In order to use cable energization at voltage peak, these transient overvoltages may not become larger than allowed limits.

For OHL without an UGC, it has normally been accepted to energize without any synchronization, neither at zero voltage nor voltage peak. It is therefore already widely accepted to have acceptable overvoltages during energization in voltage peak. The method of studying possible risks, is by performing an insulation co-ordination study, with a thorough energization study [7]. The difference when energizing a cable and an OHL is the large line current, due to the cable capacitance. This however, can be studied for lines with UGC as for OHL's. Here, one should only be aware that there might be a need for modeling larger parts of the system, when many cables are included [8].

By performing such a switching study early in the planning process of the cable line, it is possible to identify if the cheaper and more practical solution of synchronized energization at voltage peak is applicable.

IV. Case Studies

For performing insulation co-ordination study, using synchronized point on wave energization at voltage peak, the system has to be modeled at the respective voltage level, as well as parts of the below voltage level. This is for ensuring all affect from possible cable lines at the lower voltage level. For this, it is chosen to use en EMT type program, with a frequency dependent model of all cables up to 3 substations away, on the respective voltage level, and up to 2 substations away on the lower voltage level. Shunt reactors are modeled as lump inductances and resistances, with mutual coupling between phase windings. Furthermore, the entire remaining surrounding network is modeled using PI-equivalents. After validation of modeling setup, it is possible to perform a full insulation co-ordination study, similar to [7].

A. *Case I – long line double system*

Case I is based on a new 400 kV cable line in Denmark, called the Lillebaelt connection. This cable connection is shown in Fig. 4.

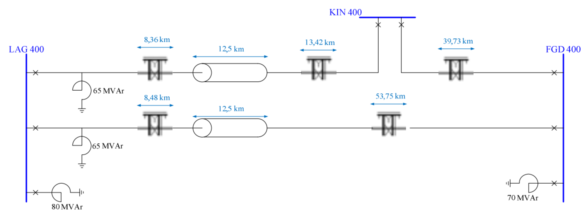

Fig. 4 The Lillebaelt connection for case study I. This line is a combination of OHL and UGC, where the circuit breakers are placed at the substations LAG400, KIN400 and FGD400. Each of these substations also has a 150 kV voltage connection.

When performing the insulation co-ordination study, the circuit breaker switching was performed in sequence, where each breaker was closed at voltage peak. The transient voltages at all three busbars, and at each transition between OHL and UGC are analyzed. The energization for all three phases is performed as a multirun case, with a normal distribution having a standard deviation of 3 ms. This means that each phase is energized from -0.003 s to 0.003 s compared to the point of voltage peak. The reason for this procedure is to include any possibility of mechanical delay in the circuit breakers. For each energization, only the largest peak of the transient voltage is studied and compared to the allowed maximum calculated using [7]. Three different energization scenarios are studied, as shown in Fig. 5.

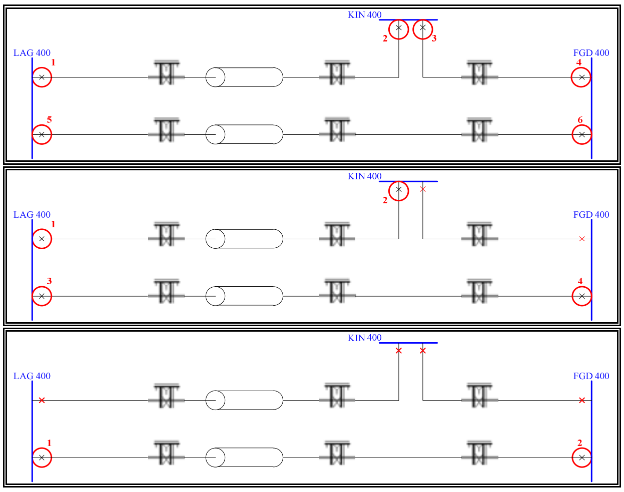

Fig. 5 Possible energization scenarios for the Lillebaelt line of study case I. The switching sequence is shown with circles and numbers

The simulation results, for the energization study, are shown in Fig. 6 - Fig. 8.

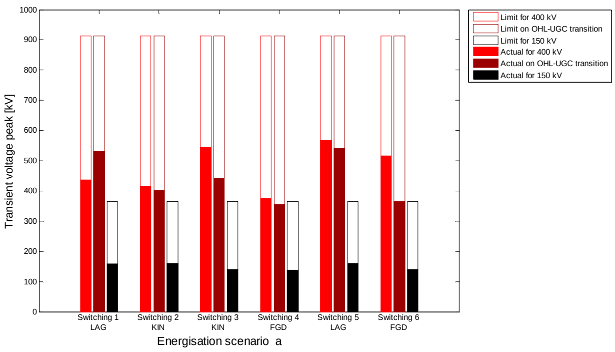

Fig. 6 Results for the first energization scenario of Case Study I, with all 6 circuit breakers.

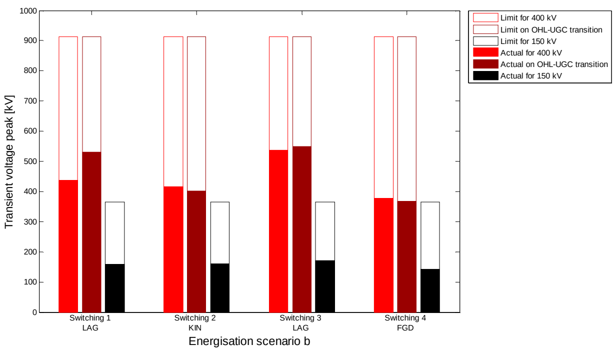

Fig. 7 Results for the second energization scenario of Case Study I, with 4 circuit breakers.

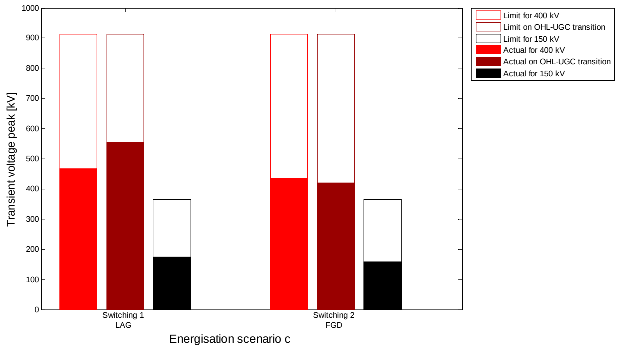

Fig. 8 Results for the third energization scenario of Case Study I, with only 2 circuit breakers.

As can be seen from the simulation results, the transient overvoltages at all three busbars, both 400 kV and 150 kV, as well as in the transitions between OHL and UGC, is much lower than allowed limits. There are therefore no overvoltage problems during synchronised energization in voltage peak.

For analysing the effect of voltage peak energization on the circuit breakers, all breaker currents are monitored during energization. The largeste transient current occurs for the breaker LAG400-FGD400 in switching scenario with all 6 breakers. This is due to the inrush current coming from the parallel UGC. When the 5th breaker is connected, the line between LAG400 and FGD 400 will draw transient current from the line LAG400-KIN400-FGD400 [9]. The largest transient breaker current is plotted in Fig. 9.

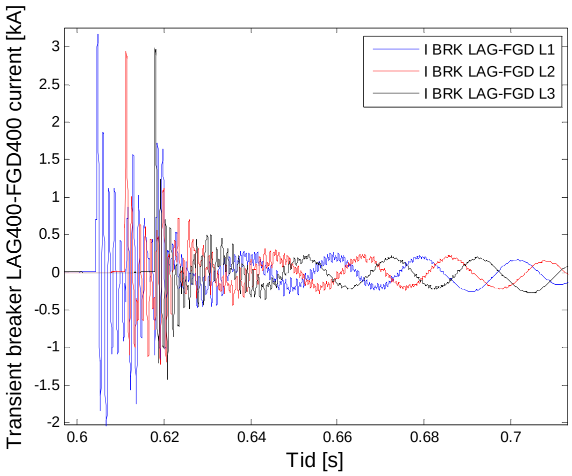

Fig. 9 Breaker current in the breaker LAG400-FGD400 from Fig. 5.

As it can be seen from Fig. 9, the transient inrush current through the circuit breakers is quite high. This however is not a problem, as it is possible to define the type of the circuit breaker, and how much inrush current the contacts can experience. When the breaker is purchased, the type needs to be designed for energization transients with currents of above 3 kA. This is normally solved by using a breaker type of class C2 [10]. It should also be noted here, that the circuit breakers are very rarely switched and the problem of damaging the breaker contacts due to the high current transients can be neglected.

The solution for study case I is therefore, that synchronised point on wave energization in voltage peak can effectively be used for removing the zero-miss phenomena.

B. *Case II – many lines, two double systems*

Case II is based on a new 400 kV cable line in Denmark, called the Kasso-Tjele connection. The connection has two OHL systems, where each OHL system has three sections of double UGC. There is therefore a total of 12 cables, each of 1.6 km, 4.5 km and 2.5 km.

The Kasso-Tjele connection is shown in Fig. 10. As for Case I, all 400 kV UGCs and OHLs in Fig. 10, and up to three substations away, are modeled using frequency dependent models, while the remaining 400 kV network in Western Denmark is modeled using PI-elements. The 150 kV system is modeled using frequency dependent models for up to two substations away, while the remaining 150 kV lines are modeled using PI-elements.

For the insulation co-ordination study of Case II, not only synchronised switching in voltage peak is analysed. Instead many combinations, including voltage peak for all phases, are used for switching moments. Phase L1 is energized for 5 different switching times, positive and negative voltage peak, 45 deg. from voltage peak, zero voltage and 45 deg. from zero voltage. The energization is therefore uniformly distributed on a 50% of a voltage period, where [11] recommends minimum of 33% of a voltage period. The energization for the remaining two phases has a normal distribution with standard deviation of 3 ms, compared to phase L1. All possible mechanical delays in the circuit breakers are thereby included.

All three phases are closed simultaneously, ±3 ms. This can produce even larger overvoltages, than when the three phases are synchronously energized.

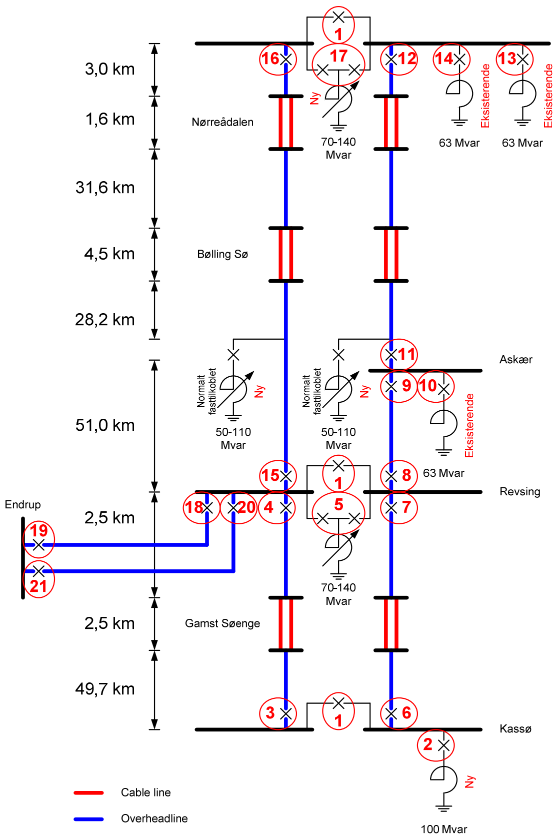

Fig. 10 The Kasso-Tjele connection for case study II. This line is a combination of a double OHL and 2 times double UGC. Each substation also has a 150 kV voltage connection.

There are only two switching scenarios for the Kasso-Tjele line, energization from south, shown in Fig. 10, and a similar energization from the north. The simulation results are shown in Fig. 11 - Fig. 12.

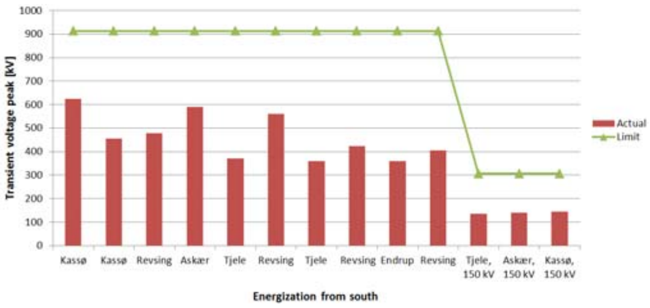

Fig. 11 Results for busbar voltages, for the energization sequence from south from south of Case Study II.

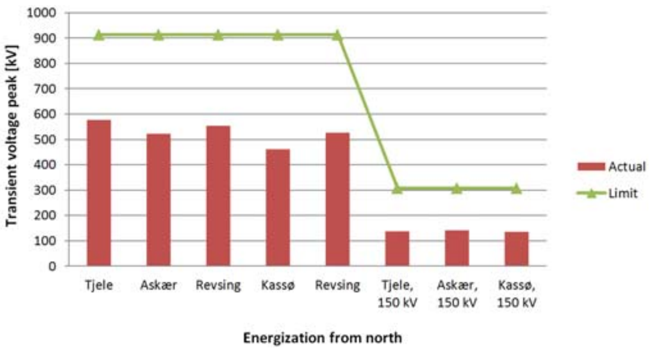

Fig. 12 Results for busbar voltages, for the energization sequence from north of Case Study II.

As for study case I, the transient voltages are much lower than the allowed limits. There is therefore no risk of having dangerous transient overvoltages during energization in voltage peak.

The results for the largest transient breaker current are shown in Fig. 13. The largest breaker current happens when the second OHL is connected (breaker number 3 in Fig. 10). Then the second line will draw transient current from the already energized parallel line.

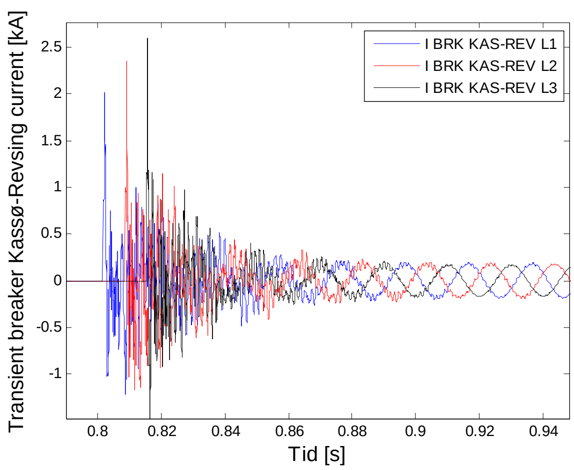

Fig. 13 Breaker current in the breaker Kassø – Revsing, #3 from Fig. 10.

As for Case I, there is high transient current in the breaker during the energization of the second line.

Therefore, for using synchronized point on wave energization in voltage maximum, there are no overvoltage problems, but the breakers should be of type Class C2, due to fast transient inrush current.

V. CONCLUSIONS

In this paper, various countermeasures for zero-miss phenomena of compensated UGC systems are discussed. One particular countermeasure, synchronized point on wave energization in voltage peak, is further described and studied. This countermeasure is attractive as it has low cost, includes no extra equipment and because switching with possible voltage peak energization is a known method from previous OHL systems. Furthermore, busbar connected shunt reactors are often energized during voltage peak, namely to minimize the DC-component. For this, the top winding of the shunt reactors already include extra insulation, for the extra transient dI/dt.

For solving the zero-miss problem, a thorough transient modelling of a large transmission system, model validation and insulation co-ordination study is discussed. It is shown, how it is possible to obtain a theoretical, practical and cost effective solution, by synchronously energizing compensated cable lines at busbar voltage peak. It is shown, due to possible mechanical delay of the breakers, that this solution cannot be used for a 100% directly compensated cable line. Theoretically the maximum is 69%, for a mechanical delay of 1.5 ms. However, due to system damping, this is often approximately 75%.

Two case studies are used for demonstrating how the transient overvoltages are below allowed limits, during energization at voltage peak.

An observation is made in the transient current of the circuit breaker. There is a very high fast transient inrush current in the breaker, which needs to be taken into account, by using a circuit breaker of type class C2.

It is shown in this paper, that using energization in peak voltage is feasible and does not give high extra costs to solve the zero-miss phenomena, although the solution requires a control scheme, ensuring point on wave energization. For using the countermeasure, an insulation co-ordination study should be performed, similar to what is described in this paper.

VI. REFERENCES

[1] F. F. da Silva, C. L. Bak, U. S. Gudmundsdottir, W. Wiechowski, M. R. Knardrupgård, "Use of a Pre-Insertion Resistor to Minimize Zero-Missing Phenomenon and Switching Overvoltages". In Proc. IEEE PES General Meeting, Calgary, Canada, July 26-30 2009.

[2] "Methods to minimize Zero-Missing Phenomenon". /Faria da Silva, Filipe; Bak, Claus; Gudmundsdottir, Unnur; Wiechowski, Wojciech; Knardrupgard, Martin. IEEE Transactions on Power Delivery, 2010, vol: PP, nr: 99, pp. 1-8.

[3] Tokyo Electric Power Company, "Joint Feasibility Study on the 400kV Cable Line Endrup-Idomlund: Final Report", April 2008

[4] T. Ohno, 2012. Dynamic study on the 400 kV 60 km Kyndbyværket-Asnæsværket Line. Denmark: Energinet.dk and Aalborg University. PhD Thesis.

[5] T. Ohno, "Operation and Protection of HV Cable Systems in TEPCO", *Global Facts, Trends and Visions in Power Industry, Swiss Chapter of IEEE PES*, April 2010. Presentation available on the web: http://www.ieee.ch/assets/Uploads/pes/downloads/1004/10042ohnoexperiencetepco.pdf

[6] U. S. Gudmundsdottir, 2010. Modelling of long High Voltage AC cables in Transmission Systems. Denmark: Energinet.dk and Aalborg University. PhD Thesis.

[7] International standard IEC 60071-1,2,4. Insulation co-ordination – definitions, principles and rules – Application guide – computational guide to insulation co-ordination and modelling of electrical networks.

[8] F. M. F. da Silva, 2011. Analysis and simulation of electromagnetic transients in HVAC cable transmission grids. Denmark: Energinet.dk and Aalborg University. PhD Thesis.

[9] F. F. da Silva, C. L. Bak, M. L. Hansen, "Back-to-Back Energization of a 60 kV Cable Network – Inrush Currents Phenomenon," in Proc. IEEE PES General Meeting, Minneapolis, USA, July 25-29 2010.

[10] IEC 62271-100: High-Voltage switchgear and controlgear – Part 100: Alternating-current circuit-breakers.

[11] IEC 60071-4: Insulation co-ordination – Part 4: Computational guide to insulation co-ordination and modeling of electrical networks.