A FACTS Device to Increase the Transmission Capacity of High-Voltage Lines under Faulted Conditions

Gunthard Orglmeister, Herbert Stemmler
Swiss Federal Institute of Technology, Power Electronics Laboratory
CH-8092 Zürich, Switzerland
orglmeister@lem.ee.ethz.ch

***Abstract* - A new FACTS device for the compensation of single line faults in high voltage AC transmission systems is presented. The application principle, two possible topologies, and the control strategies are discussed. First results are shown confirmed by both simulation and experiments on a laboratory model.**

I. Introduction

The present practice in power system operation calls for a three-phase interruption of a faulted circuit when a persistent asymmetrical fault occurs. But realizing that the majority of faults on transmission lines are single-phase faults gave rise to the idea that the conductors not affected by the fault could still be utilized for the power transmission. This would increase the availability of power transmission lines and thereby improve the transmission capacity of the network. A FACTS device[1)] could provide the means of injecting asymmetrical currents so that the transmission line appears symmetrical from the outside. The application principle for such a device is depicted in Fig. 1. In this paper the possible topologies and the control algorithm for this purpose are discussed.

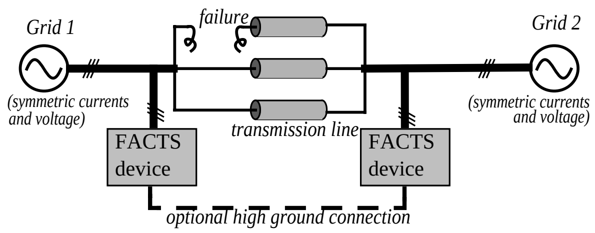

Fig. 1. The application principle of the new FACTS device

II. Concept

One of the new FACTS devices required for the current symmetrization on a power system has to be installed at each terminal of the line (as shown in Fig. 1). So, during asymmetrical faults the remaining sound conductors of the transmission line can be kept in service without affecting the system's symmetry outside the line. This objective is achieved when the two Neutral-Point-Clamped (NPC) inverters compensate for the negative and zero sequence current resulting from the asymmetrical operation of the transmission line. Substantial gain in transmission capacity is attained as a result. A 3-phase symmetrical network is assumed. If one line is interrupted, the remaining currents cause an asymmetrical load. The missing current has to be provided by the FACTS device. This can be achieved by a combination of a single phase load and a 3-phase injection. The appropriate current phasors are shown in Fig. 2. Such a concept was first proposed by [1]. In common practice the neutral point of generators and transformers in a power system are grounded. Therefore opening one phase of a transmission circuit leads to a current from the neutral point to ground, due to the zero sequence condition. In order to reduce the earth current that, in theory, could be as high as one of the phase currents, the installation of a high ground conductor is recommended in [1]. As no special insulation is needed it can easily be installed on existing transmission lines. In today's technology - where semiconductors are not available for a switching voltage over 10 kV - the FACTS devices have to be connected via coupling transformers. However in the future the structure could be substantially simplified by omitting these transformers.

1) FACTS stays for "Flexible AC transmission system"

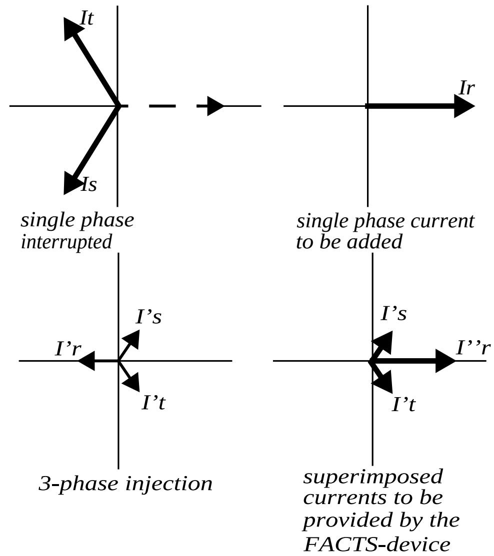

Fig. 2. Current phasors for symmetrization

A. Alternatives to high ground connection

Although it has been shown by [1], that a high ground connection fits the conventional tower configuration without additional space requirements, its installation into an existing transmission line is an important effort. Therefore an alternative approach was sought: If only one sound conductor is interrupted, it should be possible to use the two remaining conductors for a single phase transmission without relying on a transmission over earth or a high ground conductor. In the proposed configuration according to Fig. 1 (without the ground connection) the FACTS device cannot produce any zero sequence current, as the sum of the currents through its three connected wires has to be zero.

The FACTS device can only be used to compensate for the negative sequence current, produced by the interruption. However the zero sequence current can be avoided by grounding only one side of the transmission line.

B. Grounding

In most modern high voltage grids the preferred transformers topology is Yy0 or Yy0d5[1], where both neutral points are grounded by hard grounding. The reason for this grounding concept is that any overvoltage can be avoided in case of a broken and grounded sound conductor. This hard grounding can easily be replaced by an overvoltage protection that connects the neutral point to earth, if it's voltage against ground reaches a critical value (about 10% of the nominal voltage i.e.). By this modification zero sequence currents can be prevented. We can show that the potential of the neutral point of the not grounded transformer is only one third of to the voltage drop over the transmission line. This can easily be kept below 10% of the nominal line voltage.

III. Mathematical analysis

A. Analysis of phase currents and voltages

For a better understanding of the operation principle for the symmetrization, we can consider the model presented in Fig. 3. The converters are represented by voltage sources, which form - together with the coupling inductances - current sources. First we look at the voltages:

$$u_{1a} = \dot{i}_{1a} \cdot L_{T1} + u_{sa} + \dot{i}_{L2a} \cdot L_L + \dot{i}_{2a} \cdot L_{T2} \quad , \\ + \dot{i}_{2a} \cdot L_2 + u_{2a} + u_{20}$$

$$\left(\dot{i} = \frac{di}{dt}\right) \tag{1}$$

$$u_{1b} = \dot{i}_{1b} \cdot L_{T1} + u_{sb} + \dot{i}_{L2b} \cdot L_L + \dot{i}_{2b} \cdot L_{T2} \\ + \dot{i}_{2b} \cdot L_2 + u_{2b} + u_{20} \tag{2}$$

$$u_{1c} = \dot{i}_{1c} \cdot L_{T1} + u_{sc} + \dot{i}_{L2c} \cdot L_L + i_{2c} \cdot L_{T2} \\ + \dot{i}_{2c} \cdot L_2 + u_{2c} + u_{20} \tag{3}$$

As the inner voltages of the grid can often not be accessed, we can look instead to the connecting voltages $u_{1La,b,c}$ and $u_{2La,b,c}$:

$$u_{L1a} = u_{sa} + \dot{i}_{L2a} \cdot L_L + u_{L2a} + u_{20} \tag{4}$$

$$u_{L1b} = u_{sb} + \dot{i}_{L2b} \cdot L_L + u_{L2b} + u_{20} \tag{5}$$

$$u_{L1c} = u_{sc} + \dot{i}_{L2c} \cdot L_L + u_{L2c} + u_{20} \tag{6}$$

The basic relations between the currents are:

$$i_{1a} + i_{WR1a} = i_{La} = i_{2a} - i_{WR2a} \tag{7}$$

$$i_{1b} + i_{WR1b} = i_{Lb} = i_{2b} - i_{WR2b} \tag{8}$$

$$i_{1c} + i_{WR1c} = i_{Lc} = i_{2c} - i_{WR2c} \tag{9}$$

1) d5 is an compensation coil, that is not connected to any transmission line

We assume that the inner voltages of the connected grids are symmetrical and therefore free of zero sequence components:

$$u_{1a} + u_{1b} + u_{1c} = 0 \text{ and } u_{2a} + u_{2b} + u_{2c} = 0 \tag{10}$$

The used topology (without ground connection) forces the grid currents to be free of zero sequence components as well:

$$i_{1a} + i_{1b} + i_{1c} = 0 \text{ and } i_{2a} + i_{2b} + i_{2c} = 0 \tag{11}$$

As the zero points of the converters are not grounded, the converter currents are free from zero sequence components:

$$i_{WR1a} + i_{WR1b} + i_{WR1c} = 0 \text{ and} \\ i_{WR2a} + i_{WR2b} + i_{WR2c} = 0 \tag{12}$$

With equations (7) to (9) and (11) we get:

$$i_{La} + i_{Lb} + i_{Lc} = 0 \;{}^{2)} \tag{13}$$

However the voltages are not all free of zero sequence components:

$$\dot{i}_{La} \cdot L + \dot{i}_{Lb} \cdot L + \dot{i}_{Lc} \cdot L = 0 \tag{14}$$

$$\dot{i}_{La} \cdot L = 0 = u_{TLa} \text{ and} \\ \dot{i}_{Lb} \cdot L = u_{TLb} = -\dot{i}_{Lc} \cdot L = u_{TLc} \tag{15}$$

$$\text{but: } u_{Sa} + u_{Sb} + u_{Sc} \neq 0 \,,\; u_{sb} = u_{sc} = 0 \tag{16}$$

Because of the asymmetrical voltage over the transmission line $u_{TLabc}+u_{Sabc}$ the neutral point of the not grounded grid voltage U_2 will see an sinusoidal voltage u_{20} according to the following relation:

$$u_{20} = \frac{u_{Sa}}{3} \tag{17}$$

$$u_{Sa} = \frac{3}{2}(u_{L1a} - u_{L2a}) \tag{18}$$

If both connecting voltages $u_{L1a,b,c}$ and $u_{L2a,b,c}$ have the same amplitude and differ only by the phase angle $\Delta\varphi$, equation (18) can be simplified to:

$$u_{Sa} = 3 \cdot \hat{u}_{La} \sin\left(\frac{\Delta\varphi}{2}\right) \tag{19}$$

Therefore the voltage overlay of the neutral point u_{20} is only one half of the voltage drop over the line. This is a value that can easily be dealt with without modifying the isolation of the towers and transformers.

B. Pointer representation

For the pointer representation we have to consider both side of the compensator separately. As each pointer has to be based on a unit pointer based on a phased looked loop (PLL), we use for all signals of the grid 1 and the converter 1 a PLL based on the grid voltage u_1.[3]

2) The fact that the line current is free of zero sequence components does not mean, that it is a symmetric three phase current.

3) The index $^{(1)}$ in the following equations shows that the designated pointers are based on the PLL of grid 1.

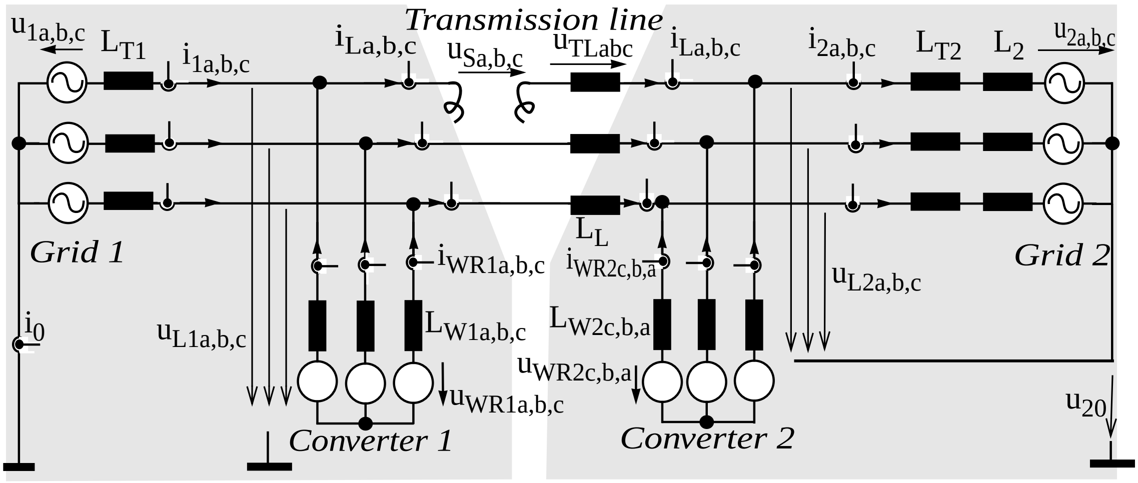

Fig. 3. For a mathematical analysis the converters are represented as voltage sources. They are connected to the transmission line either by the decoupling inductances or transformers ($L_{T1,2}$). - This makes mathematically no difference. The power grids are represented by their inner voltages and reactances. The grid 1 is defined as a strong grid, so its inner inductance is significantly smaller than the coupling inductance L_{T1} and therefore omitted

Based on the equations (7) to (9), we can build the pointer for the line currents $i_{La,b,c}$:

$$\underline{I}_L^{(1)} = \underline{I}_1^{(1)} + \underline{I}_{WR1}^{(1)} \tag{20}$$

I_L can be split into an active and a reactive part:

$$\underline{I}_L^{(1)} = I_{Ld}^{(1)} + jI_{Lq}^{(1)} \tag{21}$$

Both parts can be splitted into a constant and an oscillating part.

$$I_{Ld}^{(1)} = I_{Ldkonst}^{(1)} + \Delta I_{Ld}^{(1)} \text{ and } I_{Lq}^{(1)} = I_{Lqkonst}^{(1)} + \Delta I_{Lq}^{(1)} \tag{22}$$

During normal three phase transmission the oscillating parts $\Delta I_{Ld}^{(1)}$ and $\Delta I_{Lq}^{(1)}$ disappear. During the interruption of one sound conductor and the forced single phase transmission, those oscillating parts oscillate with double the frequency of the grid voltages. They represent the negative sequence current. We have to force the converter to produce those negative sequence currents in order to allow only positive sequence currents in the connected grid.

$$\underline{I}_{WR1}^{(1)} = \Delta I_{Ld}^{(1)} + j\Delta I_{Lq}^{(1)} \text{ and } \underline{I}_1^{(1)} = I_{Ldkonst}^{(1)} + jI_{Lqkonst}^{(1)} \tag{23}$$

For grid 2 and converter 2 the equivalent relations are valid for pointers based on a PLL based on the grid voltage u_2.

C. Reactive power compensation

In addition to the symmetrization of the grid currents the compensator can also be used to introduce reactive currents and to improve the power factor of the line. The converter current and the grid current presented in equation (23) get as additional term the reactive compensation current:

$$\underline{I}_{WR1}^{(1)} = \Delta I_{Ld}^{(1)} + j(\Delta I_{Lq}^{(1)} + I_{q1komp}^{(1)}) \text{ and}$$
$$\underline{I}_1^{(1)} = I_{Ldkonst}^{(1)} + j(I_{Lqkonst}^{(1)} + I_{q1komp}^{(1)}) \tag{24}$$

D. Power flow

During normal power transmission over a three phase line the transmitted power depends on line parameters (reactance and resistance), the voltage of the connected grids and the phase angle between these two grids. In the simplified case of a line without losses (without resistance) the following relation is valid:

$$P_{1,2normal} = \frac{3}{2} \cdot \frac{U_1 \cdot U_2}{\omega L} \cdot \sin(\varphi) \tag{25}$$

φ is the phase angle between the two lines. U_1 and U_2 are the amplitudes of the connected grid voltages. It is assumed that they have the same frequency and about the same amplitude. If a single phase interruption of one line occurs, the transmitted power is not constant any more but it oscillates with double the grid voltage frequency. However it can be shown that the average transmitted power is half the power transmitted without interruption:

$$P_{1,2interr} = \frac{3}{4} \cdot \frac{U_1 \cdot U_2}{\omega L} \cdot \sin(\varphi) \tag{26}$$

While no compensator is active, we can consider the line inductance L_{TL} together with the transformer inductance $L_{T1,2}$ and the inner inductance of the grid L_2 as one single inductance L. As soon as the converter is active all inductances but the line inductance L_{TL} see a three phase current. For the calculation of the transmitted power we have therefore to consider both parts separately. During active compensation the transmitted power is:

$$P_{1,2interr,comp} = \frac{3}{2} \cdot \frac{U_1 \cdot U_2}{\omega(L_{T1} + \mathbf{2} \cdot L_{TL} + L_{T2} + L_2)} \cdot \sin(\varphi) \tag{27}$$

The transmitted power can further be influenced by the reactive power compensation discussed above. By the reactive power compensation it is actually possible to keep the power flow unchanged before and during the interruption.

However the maximum acceptable currents in the line have to be considered.

IV. Topology

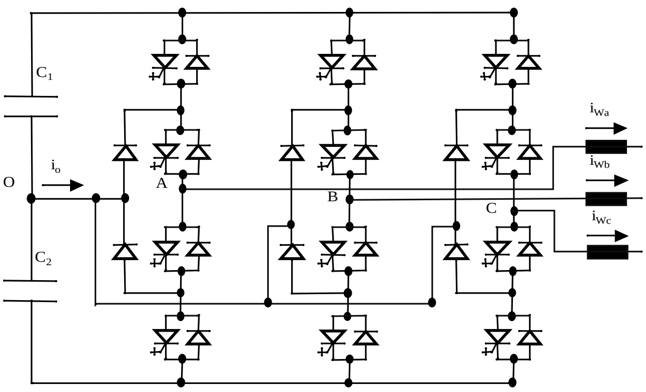

Fig. 4. The topology of one of the FACTS devices. Both are identical 3-phase 3-level converters without ground return.

Fig. 4 illustrates the topology of the 3-level converter that has been considered for this application. By using a 3 level converter the harmonic distortion of the concerned power grids can be kept low. The power flow to and from the connected networks is constant while the power flow over the damaged transmission line is a single phase transmission and ergo oscillating with double the frequency of the network. The capacitors must accommodate the transmitted energy for half a period (0.01 s). The valves must deal with currents and voltages in the range of the currents and voltages of the transmission line. As this is not yet feasible with today’s technology, the converter has to be connected to the transmission line by the means of a transformer. As the transmitted current might be asymmetrical the best results are produced with a 5-leg transformer in the Yy0 topology.

For the alternative topology with a high ground connection connected to the neutral points of the converters a slightly different topology has to be used: As the high ground current charges and discharges also the dc side, a 4th leg to control the dc side neutral potential has to be added[2].

V. Control

Three main topics had to be considered for the control of the investigated FACTS device:

-) In case of a line break the device must immediately provide the compensation currents according to Fig. 2. The transition to this state has to be realized within one or two periods of the grid voltage.

-) The neutral point of the three level inverter has to be balanced. This is especially demanding during an asymmetrical line fault, as the dc-side voltage oscillates with 100 Hz, because energy has to be stored in the DC-link capacitors during half a period of the grid voltage.

-) Under normal operation conditions i.e. the transmission line has no fault, the device may be used to compensate the reactive power of the line.

Two different control techniques have been evaluated:

A. A classical control structure

The first - more classical control structure - is depicted in Fig. 5. The current $\vec{I}_1$ is measured at the connection point and separated into the positive sequence part and the negative sequence part. With a PI-control it is controlled to be zero.

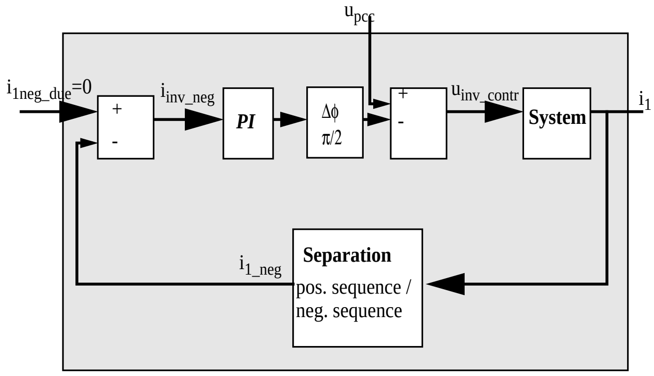

Fig. 5. A classical control structure: The line current i_1 is separated by means of a moving average filter into the positive and negative sequence current. The converter is controlled to absorb the same negative sequence current in order to compensate for it.

The disadvantage of this control is the fact that the separation of positive and negative sequence currents, that is realized by passing the pointer of the current ($I_{1d,q}$) through a moving average filter, produces a delay of at least half a period of the analysed current. This delay makes the whole control quite slow and the symmetrization of the grid currents after a line break takes about two to three periods of the grid voltage to restore symmetric conditions.

B. A discrete Dead Beat Control with integrating oscillators

A better approach is the use of integrating oscillators together with a Dead Beat Control. This concept is discussed in detail in[4]. The three-phase currents are transformed into rotating pointers (α, β -presentation). These signals are passed to integrators that rotate with the frequency that should be controlled. In the present application we have one oscillator that rotates with the base frequency of the grid (to control the positive sequence currents) and an other one that rotates with the same frequency, but in the opposite direction (to control the negative sequence currents). 1)

Generally an oscillator produces for the input signal:

$$\vec{x}(t) = e^{j(\omega_1 t + \varphi)} \text{ the output } \vec{y}(t) = K_I t e^{j(\omega_1 t + \varphi)} \qquad (28)$$

The Laplace transformation of its transfer function is:

$$O(s) = \frac{\vec{Y}(s)}{\vec{X}(s)} = \frac{K_I}{s - j\omega_1} \qquad (29)$$

1) Further oscillators might be added to control the harmonic distortion in the line

For the implementation together with a Dead Beat control a discrete time version of the transfer function of the oscillator is needed:

$$O(z) = \frac{K_I T e^{j\omega_1 T}}{z - e^{j\omega_1 T}} \tag{30}$$

The sum of the outputs of the integrating oscillators represents the current to be generated by the converter. After building the difference to the actual converter current it is passed to the Dead Beat control.

If the system parameters - in our case mainly the value of decoupling inductance - are known with good accuracy, a Dead Beat control can follow any step of the input signal within two time steps. In our system the sampling time depends on the conversion time of the ADCs that produce the input signals. It is much shorter than a period of the grid current, so any delay in our control depends only on the oscillators.

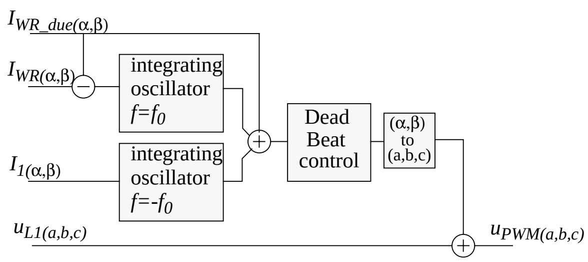

Fig. 6. The schematic of the implemented control. I_{WR_due} is the converter current, as it is required by overlaying controls, like the control of the DC-side voltage or the reactive power control. u_{PWM} is the control voltage for the PWM modulation.

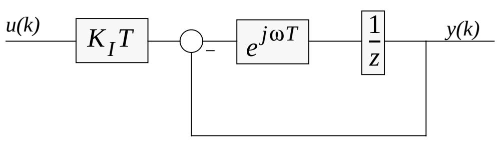

Fig. 7. The realisation of the integrating oscillator on a discrete computer system

C. Additional controls

For both control concepts additional controls had been implemented, that cannot be discussed in detail here:

A DC voltage control that keeps the DC-voltage at a desired value.

A DC side symmetrization that equals the voltage at the upper and lower DC capacitor.

A reactive current control that allows to control the reactive current in the connected grid and with it the power flow over the line.

The converter itself is controlled by PWM modulation.

VI. Results

The new device and its application had been simulated extensively using Simulink and the newly developed simulation tool PLECS [3]. The results are very encouraging. The simulation results have been confirmed by experiments on a laboratory model. It consists of a model of a 500 km 3-phase transmission line and two three-phase three-level converters and was set up for this purpose at reduced scale (440 V, 10 A). Some currents and voltages of a typical case are presented in Fig. 8 both as simulation results and as measurements at the laboratory model. As required symmetric currents in the connected grid are restored within one single period of the grid voltage.

VII. Conclusions

A FACTS element for the compensation of single phase faults in high power transmission lines has been developed and tested. With this device it is possible to increase the transmission capacity of existing AC transmission systems under faulty conditions. For the time being it has been tested only at a 5 kW laboratory model. An implementation into a working power line is not planned in the near future. The concept will become more interesting, when power electronic devices for higher voltages are available, as the costs of coupling transformers are significant.

VIII. References

[1] H. Glavitsch, M. Rahmani, “Increased transmission capacity by forced symmetrization”, *IEEE Transactions on Power Systems,* volume 13, issue 1, Feb. 1998, pages 79 -85.

[2] X. Yuan, G. Orglmeister, W. Merk, “Managing the DC Link Neutral Potential of the Three-Phase-Four-Wire Neutral-Point-Clamped (NPC) Inverter in FACTS Application” *25th Annual Conference of the IEEE Industrial Electronics Society (Iecon)* 1999, pages 571-576, vol. 2, San José, CA, USA.

[3] J. Allmeling and W. Hammer: “PLECS - Piece-wise Linear Electrical Circuit Simulation for Simulink”, *Third IEEE International Conference on Power Electronics and Drive Systems (PEDS’99)*, pages 355 -360, vol. 1, Hong Kong, July 26-29, 1999.

[4] J. Allmeling: “*Schnelle Regelung eines Aktivfilters mit niedriger Taktfrequenz für das Mittelspannungsnetz*”, chapter 7, Diss ETH, Zürich, Switzerland, 2001.

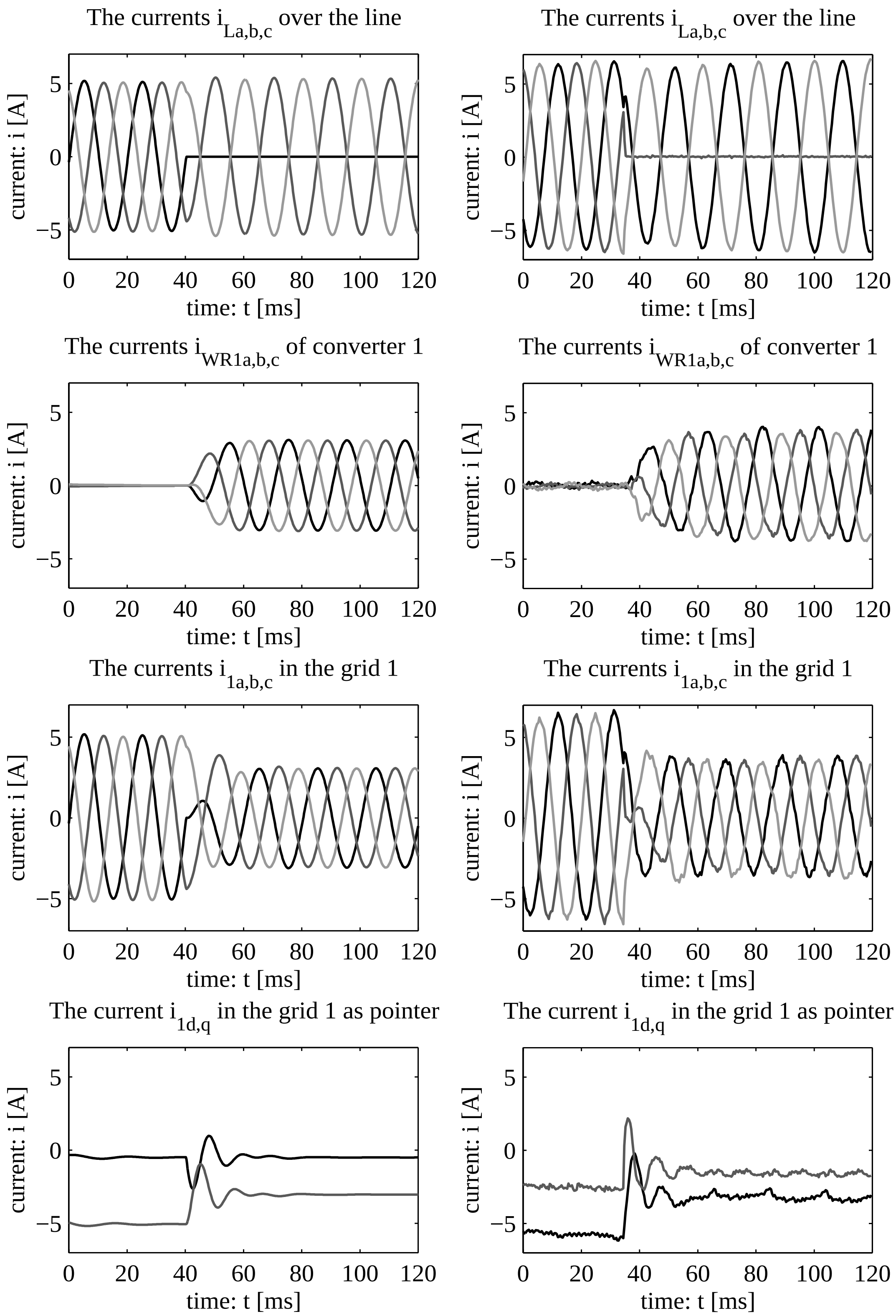

Fig. 8. The simulation results and measurements: The simulation results are depicted in the left column, while the plots of the measurements at the laboratory model are shown in the right column. The interruption occurs at about 40 ms. As the resistances and inductances for the simulation and the physical model are not identical, there is a little difference between the relations of the currents before and after the line break. The phase angle between the grid voltages of the two connected grids is 30˚. Within one period of the grid voltage the negative sequence current is compensated and only a little disturbance remains. The converter does not produce reactive power. The amplitude of the grid current i_1 drops therefore, as if the line inductance grows (see D.“Power flow”).