Energization of 380-kV Partial Networks
for the Purpose of Fast Blackstart after System Collapse

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Abstract – **In case of a major disturbance of the interconnected 380-kV system in Europe each power utility is responsible to reactivate its system operation as quickly as possible. In order to achieve a fast black-start, isolated subnetworks will be energized successively. This paper analyses the energization of a 380-kV subsystem by means of transient simulations in order to refine the concept of fast black-start.**

I. INTRODUCTION

This switching transients study has been performed to refine and update the concept of system recovery after a major disturbance in the 380-kV system from the system transients point of view.

In case of system collapse, each power utility is responsible to restore its system operation as quickly as possible [1]. The concept of black-start should take into consideration various situations caused by the disturbance:

- Outage of the whole network or part of it with a possibility of energization by coupling to the neighbor system, which is under service. If the black-start from neighbor system is not possible, then the collapsed system has to be restored by means of power plants qualified for black-start.
- Collapse of the whole interconnected system with islanded subnetworks formed having their own power generation. The islanded subnetworks must be synchronized and connected together successively.

In this paper the fast black-start of a 380-kV subsystem at no-load by means of energization from the neighbor system has been investigated. The 380/220-kV interbus transformers have to be switched off at the 220-kV voltage side and they remain connected to the 380-kV subsystem, which will be energized.

During energization none of the components of the subsystem has to be endangered by overvoltage or overcurrent. Tripping conditions have to be reviewed, so that the restoration of the system will not be delayed or prevented.

Since real-life tests with the parts of the interconnected 380-kV system in service are practically impossible, the expected switching overvoltages and current surges caused by the energization of the subsystem at no-load are investigated by means of transients simulations. Fortunately, measured voltage and current waveforms were available from similar energization tests in a 380-kV system [2], which could be used to verify the system model established for simulations [3] in principle.

II. MODELING OF THE SYSTEM

A. System Data and Configuration

The single-line diagram of the investigated 380-kV subsystem is shown in Fig. 1. The steady-state voltage rise due to capacitive charging power of lines is limited by means of compensation reactors connected to the tertiary winding of autotransformers. The total reactive power amounts to 500 Mvar at 380 kV, whereas charging power of lines results adds up to approximately 300 Mvar. The steady-state voltage magnitudes at each busbar are given in Fig. 1 for two cases with and without reactors connected. The voltage of the energization busbar BB1 is set to 400 kV. Without compensation reactors a steady-state voltage rise of maximum 4.5 % based on 400 kV is expected.

The electrical data of system components are summarized in Table 1. The data of overhead lines and reactors are given in Fig. 1.

Table 1. Electrical data of system components

Source network		
voltage (rms)	(kV)	400
short-circuit power at BB1	(GVA)	10..15
ratio X_0/X_1		3.3
ratio R_1/X_1		0.1
ratio R_0/R_1		3.0
Autotransformers (single-phase units)		
rated voltage of windings	(kV)	231 / 133 / 30
rated power of windings	(MVA)	333 / 333 / 66
impedance voltages 1-2, 1-3, 2-3	(%)	15.2 / 14.9 / 10.9
Overhead lines, reactors refer to Fig. 1		

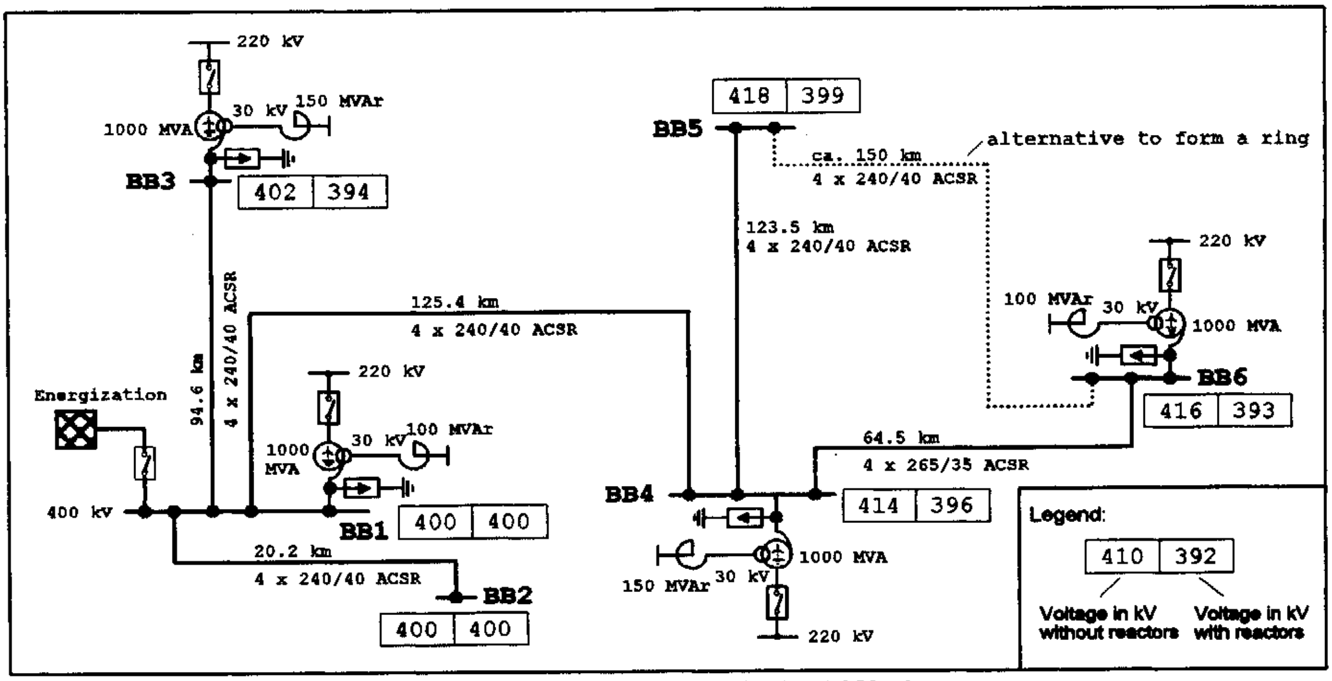

Fig. 1. Single-line diagram of energized 380-kV subsystem

The surge arresters indicated in Fig. 1 are of metal-oxide type and protect the transformers and substation equipment.

Under steady-state conditions an inductive current of 215 A (rms) flows from the source into the network, when all reactors are connected to the transformers. Without reactors it amounts to a capacitive value of 448 A (rms).

B. Models of the Components

Various factors play important role in the switching transients of such a relatively complicated network. The models of system components should accurately reproduce the transients effected by the factors. Main factors are:

- travelling wave effects and damping on lines
- saturation and residual flux of transformers
- source network representation
- circuit breaker closing times.

ATP-EMTP program [4] is used to model and simulate the 380-kV system. Transmission lines are represented by Jmarti line model [4,5], which takes into consideration the frequency dependence of line parameters. Constant-parameter, distributed line model [4] was shown to be inadequate to replicate the attenuation of surges, when models have been verified by means of measurements [2,3].

The autotransformers are represented as single-phase units by coupled RL elements with the hysteretic inductors connected to the tertiary winding terminals to model the saturation and residual flux in the core. Short-circuit (s.c.) and no-load measurements (tertiary winding) were available from the manufacturer. Autotransformers of similar size produce inrush currents (HV side excitation) with peak values about 0.8..1.5 pu based on $\sqrt{2}\cdot$ rated current of transformer [7]. In this study, the saturation characteristic has been extended such that peak inrush current of 1 pu is realized without residual flux. The equivalent winding capacitances are added as lumped elements to the winding terminals.

The source network is represented by its positive and zero sequence short-circuit (s.c.) impedance. Alternatively, for comparison purpose a resistive branch representing the surge resistance of the feeding line has been added parallel to short-circuit impedance in accordance with [6]. This representation has been proven to give accurate results in the previous study [3].

The pole span of the closing circuit breaker (c.b.) is assumed to be 5 ms. For comparison, also a pole span of 2 ms is used. The circuit breaker poles are represented by a *statistic* switch with closing times determined according to uniform distribution [4].

III. STUDIED CASES

The goal of this energization study is to determine the maximum overvoltages in the system, amplitudes of energization currents and energy absorbed by surge arresters, when the complete subsystem shown in Fig. 1 is energized.

Each studied case consists of 150 energizations performed by changing the closing times of c.b. poles randomly according to uniform distribution. In order to cover a wide spectrum of overvoltages and overcurrents, the first pole is assumed to close within one period (20 ms) and other two poles follow as slave the first pole randomly within 5ms/2ms.

The studied cases can be characterized as follow:

a) Effect of source network representation with short-circuit power of 10 GVA/15 GVA;
b) Influence of residual flux of transformers on switching surges;
c) Energization with and without compensation reactors;
d) Energization with additional metal-oxide surge arrester installed at BB5;
e) Effect of Forming a closed ring among substations BB4, BB5 and BB6 to avoid an open line end at BB5;
f) Influence of the pole span of the closing c.b. 5 ms/2 ms.

For the case b) it is assumed that the residual flux Φ_{rem} in the core is about 60 % of the rated flux. The residual flux pattern in the tertiary winding is chosen as

winding a–b : $-\Phi_{rem}$ (Φ_{rem} = 81 Vs)
winding b–c : ≈ 0
winding c–a : $+\Phi_{rem}$.

which is obtained by switching-off simulation of the transformer. As worst-case the same flux pattern is applied to all four transformers. Alternatively, residual flux is taken into account at only two transformers at BB1 and BB6.

IV. COMPUTATION RESULTS

The effect of source network representation on the maximum overvoltages and overcurrents is summarized in Table 2 for the case with all four transformers having residual flux. The pu-values of overvoltages are based on $\sqrt{2}\cdot U_m / \sqrt{3}$, where U_m = 420 kV is the highest voltage for equipment [8]. Maxima of voltage are given in kV. The pu-values of overvoltages are shown in parenthesis.

As it can be concluded from Table 2, the increase of short-circuit power of the source, results in higher peak energization current and line current (BB1-BB4). The overvoltage magnitudes are not effected significantly.

Table 2. Summary of maximum overvoltages and line currents depending on source representation

description	residual flux at all 4 transformers, pole span=5 ms, arresters acc. to Fig.1		
source representation	s.c. power 15 GVA	s.c. power 15 GVA, R_s	s.c. power 10 GVA
$v_{ph\text{-}earth}$ at BB1	570 (1.66)	495 (1.44)	597 (1.74)
$v_{ph\text{-}earth}$ at BB2	589 (1.72)	498 (1.45)	615 (1.79)
$v_{ph\text{-}earth}$ at BB3	641 (1.87)	600 (1.75)	621 (1.81)
$v_{ph\text{-}earth}$ at BB4	665 (1.94)	649 (1.89)	671 (1.96)
$v_{ph\text{-}earth}$ at BB5	1127 (3.29)	1046 (3.05)	1073 (3.13)
$v_{ph\text{-}earth}$ at BB6	642 (1.87)	638 (1.86)	640 (1.87)
i_{max} closing c.b.	10.1 kA	9.70 kA	8.89 kA
i_{max} BB1-BB4	4.86 kA	4.65 kA	4.44 kA

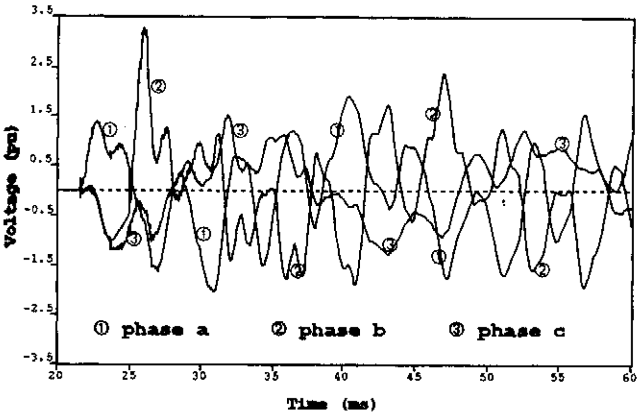

Fig. 2. Waveforms of phase-to-earth voltages at BB5 belonging to the maximum overvoltage case

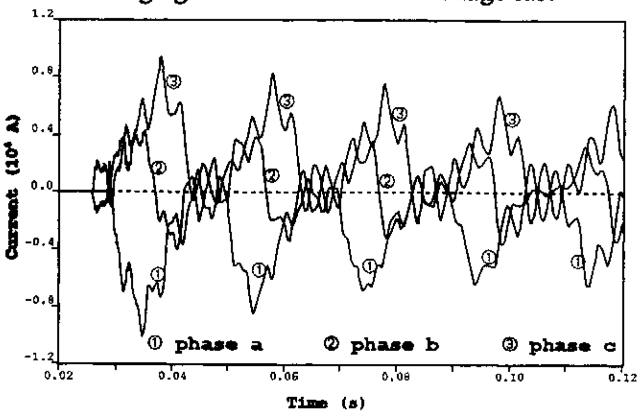

Fig. 3. Waveforms of the closing c.b. current belonging to the maximum peak current case

The overvoltages are comparatively lower only in the modeling alternative (3rd column of Table 2) with additional surge resistance R_s parallel to s.c. impedance of the source network. As a result of these studied cases, the source network is modeled with only s.c. impedance corresponding to s.c. power of 15 GVA in the following computations.

Fig. 2 and 3 show referring to 2nd column of Table 2 the voltage waveforms at BB5 belonging to the maximum overvoltage case and maximum energization line current flowing into the network, respectively.

Table 3. Summary of maximum overvoltages and line currents depending on the residual flux of transformers

description	source s.c. power 15 GVA, pole span=5 ms, arresters acc. to Fig.1		
residual flux	4 transformers	2 transform. BB1, BB6	none of transformers
$v_{ph\text{-}earth}$ at BB1	570 (1.66)	547 (1.60)	558 (1.63)
$v_{ph\text{-}earth}$ at BB2	589 (1.72)	587 (1.71)	592 (1.73)
$v_{ph\text{-}earth}$ at BB3	641 (1.87)	641 (1.87)	641 (1.87)
$v_{ph\text{-}earth}$ at BB4	665 (1.94)	664 (1.94)	665 (1.94)
$v_{ph\text{-}earth}$ at BB5	1127 (3.29)	1127 (3.29)	1128 (3.29)
$v_{ph\text{-}earth}$ at BB6	642 (1.87)	641 (1.87)	641 (1.87)
i_{max} closing c.b.	10.1 kA	8.41 kA	6.69 kA
i_{max} BB1-BB4	4.86 kA	4.05 kA	3.49 kA

From the results summarized in Table 3 it can be concluded that the residual flux of transformers does not effect overvoltage amplitudes. The peak energization current i_{max} flowing through c.b. increases with the number of transformers and with the residual flux.

The peak current flowing from the neighbor system into the energized system through the connecting line and the high current flowing into line BB1–BB4 would probably excite the distance relays protecting these lines. The threshold rms value for overcurrent excitation will be exceeded, but the rms value obtained by multiplying the average value of the rectified current with the form factor 1.11 will clearly decrease below this value before the relay trips the line.

The simulation results of additional cases related mainly to the high overvoltage magnitudes at BB5 are summarized in Table 4.

The maximum overvoltage at the open line end (BB5) is clearly higher than switching impulse co-ordination withstand voltage of 913 kV (2.7 pu based on $\sqrt{2}\cdot 420kV/\sqrt{3}$) specified by the power utility [8,9]. Both measures – installation of an additional surge arrester or forming a ring by including the overhead line BB5 - BB6 – would decrease the maximum overvoltage magnitude below 2.7 pu. The energy absorbed by the additional surge arrester at the end of line BB4-BB5 is computed as 634 kWs, which is uncritical. Installation of an additional surge arrester at BB5 is the more effective measure.

The cumulative probability distribution of overvoltages at BB5 for three different studied cases is shown in Fig. 4.

Fig. 5 compares voltage waveforms at BB5 with and without surge arrester at BB5. Current of the surge arrester and energy absorption are shown in Fig. 6 and Fig. 7, respectively.

Also a smaller pole span (2 ms) of the closing c.b. should reduce the maximum overvoltage to a permissible value (see right-most column of Table 4).

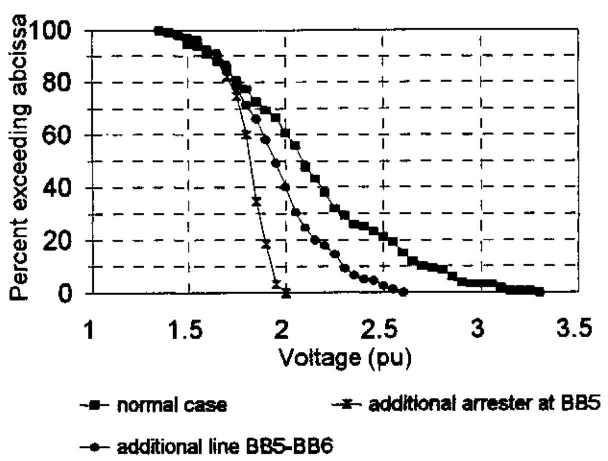

Fig. 4 Cumulative probability distribution of overvoltages at BB5 for the various cases

In order to illustrate the surge arrester duty during energization, they have been disconnected and the simulation results are given in 5th column of Table 4. It can be concluded that the arresters limit the overvoltages at approximately 2 pu as expected All installed arresters would operate during black-start.

The compensation reactors do not have any significant influence on the switching surges within 1..1½ period as compared in Fig. 8. The overvoltage and overcurrent values (see 2nd column of Table 4) do not differ from the case with reactors included (2nd column of Table 3).

Overvoltage magnitudes at the 220-kV terminals of transformers have not been studied in detail, because the surge arresters at the 220-kV side are not modeled. Additionally, capacitive surge transfer capability of those autotransformers could not be taken precisely into account. The statistical analysis shows that the overvoltages remain below 2.1 pu based on $\sqrt{2}\cdot 220kV/\sqrt{3}$ at all transformers.

Table 4. Maximum overvoltages and overcurrents caused by various effects

case description	residual flux at all four autotransformers, surge arrester acc. to Fig. 1, source s.c. power 15 GVA				
	c.b. pole span = 5 ms				pole span = 2 ms
	all comp. reactors disconnected	additional surge arrester at BB5	additional line betw. BB5-BB6	all surge arresters disconnected	with compensation reactors
$v_{ph\text{-}earth}$ at BB1	572 (1.67)	537 (1.57)	605 (1.76)	636 (1.85)	530 (1.55)
$v_{ph\text{-}earth}$ at BB2	614 (1.79)	591 (1.72)	646 (1.88)	684 (1.99)	577 (1.68)
$v_{ph\text{-}earth}$ at BB3	652 (1.90)	641 (1.87)	655 (1.91)	838 (2.44)	623 (1.82)
$v_{ph\text{-}earth}$ at BB4	681 (1.99)	659 (1.92)	661 (1.93)	841 (2.45)	638 (1.86)
$v_{ph\text{-}earth}$ at BB5	1201 (3.50)	677 (1.97)	889 (2.59)	1156 (3.37)	901 (2.63)
$v_{ph\text{-}earth}$ at BB6	656 (1.91)	638 (1.86)	663 (1.93)	854 (2.49)	628 (1.83)
i_{max} closing c.b.	10.4 kA	10.1 kA	9.59 kA	10.1 kA	9.68 kA
i_{max} BB1-BB4	4.95 kA	4.61 kA	4.66 kA	4.88 kA	4.41 kA

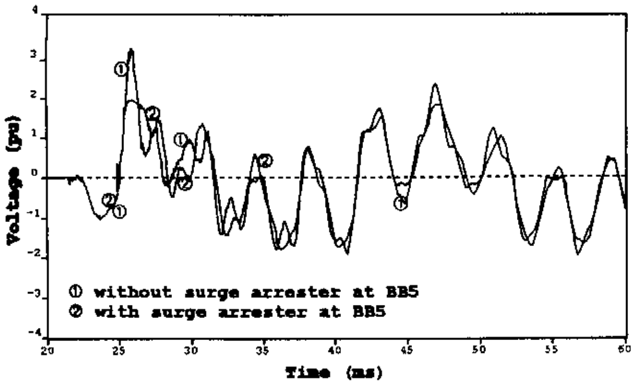

Fig. 5. Comparison of waveforms of the maximum overvoltage at BB5 with and without surge arrester

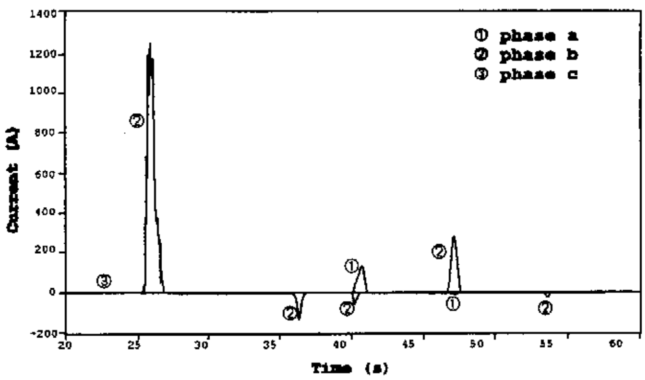

Fig. 6. Current waveforms of the surge arrester at BB5 belonging to the maximum overvoltage case

V. CONCLUSIONS

The fast black-start of a 380-kV subnetwork at no-load by means of energization from the neighbor system has been studied. Four 1000-MVA, 380/220-kV autotransformers at no-load remain connected to the energized system. Compensation reactors of total reactive power of 500 Mvar are connected to the tertiary windings of transformers.

The maximum current amplitudes at the energization busbar depend on the number of transformers, residual flux conditions and closing times of c.b. poles. The s.c. power of the source network effects also the current amplitudes, i.e. 50 % increase of s.c. power causes approximately 13 % rise of the switching current.

Since the overvoltage and overcurrent magnitudes vary significantly by the closing times of c.b. poles, statistical analysis with 150 energizations per case has been performed. As worst-case pole span of 5 ms selected. Smaller pole span (2 ms) causes significant reduction of overvoltages in the whole system.

The maximum overvoltages occur as expected from wave propagation theory at the open end of relatively long line (123.5 km) from BB4 to BB5. The metal-oxide surge arresters installed in the system to protect transformers and substation equipment limit overvoltages considerably to approximately to 2 pu based on $\sqrt{2}\cdot 420\text{kV}/\sqrt{3}$. Particularly, an additional surge arrester at BB5 plays important role to reduce the overvoltage from impermissible value of 3.3 pu down to 2 pu.

Alternatively, the line BB5 - BB6 may be included in the energized system to form a ring and thus to eliminate high voltage amplitudes caused by reflections at the open end.The compensation reactors connected to the tertiary windings of autotransformers do not effect switching surges and consequently level of overvoltages remain almost the same.

VI. REFERENCES

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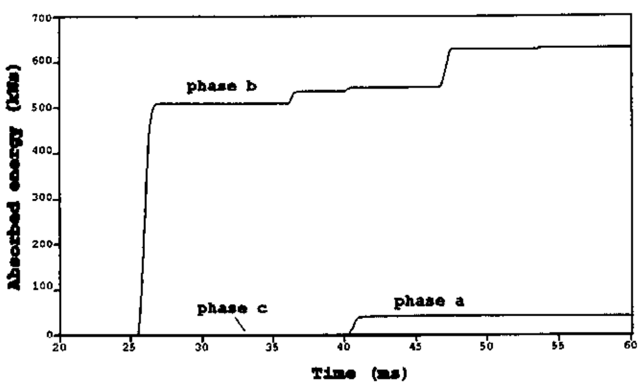

Fig. 7. Energy absorbed by the surge arrester at BB5 belonging to the maximum overvoltage case

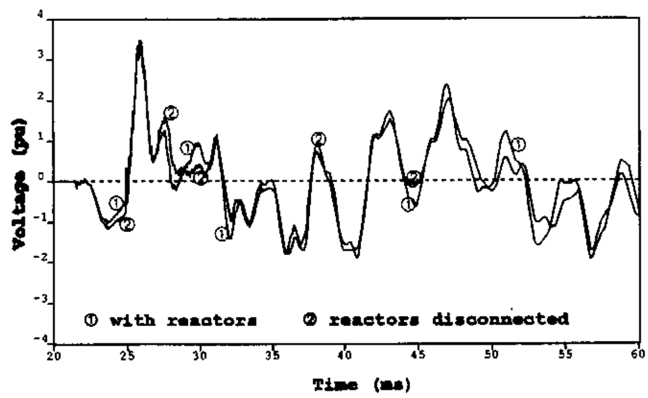

Fig. 8. Comparison of voltage waveforms for the cases with and without compensation reactors

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