Switching Overvoltages on A Pipe in A Gas-Insulated Substation

A. Ametani N. Nagaoka N. Mori K. Shimizu
Doshisha University
Kyoto 610-03, Japan
Kajima Const. Co.
Tokyo, Japan

Abstract — **This paper investigates switching overvoltages on pipes of gas-insulated buses in a gas-insulated substation. The pipe overvoltage increases as the number of the buses connected to the source side of a circuit breaker increases, and the overvoltage decreases as the number of the buses connected to the load side increases. The overvoltage significantly depends on a pipe grounding condition. The severe switching overvoltage on the pipe is strongly affected by the inductance of the grounding wire of the pipe and arresters.**

keywords : Switching surge, gas-insulated bus, grounding, arrester, EMTP

1. Introduction

A number of gas-insulated substations have been constructed and in services. The substations are of complex configuration with a number of gas-insulated buses. A bus arrangement is changed by disconnectors (DS) and circuit breakers (CB) corresponding to power system operation connected to the substation. The DS and CB operation produces switching overvoltages in the substation.

It has been well known that a high switching overvoltage appears in an overhead line with an infinite source due to CB operation /1/. A recent paper informed that a severe switching overvoltage appeared in a cable sheath when a number of cables were connected to the bus to which the CB was connected /2/. A similar situation is expected more often in a gas-insulated substation.

The present paper investigates switching overvoltages on the pipe of a gas-insulated bus, which is a kind of a cable, in a gas-insulated substation based on an EMTP simulation /3/. The gas-insulated substation is represented with a combination of gas-insulated buses. The buses are modeled either by a single-core coaxial cable or by a 3-phase pipe-type cable in the EMTP. At first, the effect of the number of buses on a pipe overvoltage is investigated in a simple circuit configuration together with the effect of a grounding condition of the pipe and arresters. Then, an EMTP simulation is carried out in an actual complex substation. The effect of the closing sequence and bus connection is investigated.

2. Model Circuit

Fig. 1 illustrates a cross-section of a gas-insulated (GI) bus which is modeled as an overhead pipe-type cable in an EMTP simulation. The parameters of the GI bus are:

(a)275kV GI bus (1pu=224.5kV)

$R1=567$, $R2=580$, $r1=31.5$, $r2=46.5$, $d=317$, $h=1000$ [mm] ; $\rho p=7.53\times10^{-8}\Omega m$, $\mu p=1$, $\varepsilon p=1.15$, $\rho=2.2\times10^{-8}\Omega m$, $\mu=1$, $\varepsilon=1$; $\theta 1=0^\circ$, $\theta 2=180^\circ$, $\theta 3=270^\circ$

(b)154kV GI bus (1pu=125.74kV)

$R1=365$, $R2=380$, $r1=45.0$, $r2=60.0$, $d=195$, $h=1000$ [mm] ; $\rho p=1.3\times10^{-7}\Omega m$, $\mu p=1000$, $\varepsilon p=1.21$, $\rho=2.8\times10^{-8}\Omega m$, $\mu=1$, $\varepsilon=1$; $\theta 1=0^\circ$, $\theta 2=180^\circ$, $\theta 3=270^\circ$

Fig. 2 illustrates a model circuit of a basic investigation. In the figure, Ls=20mH is a source inductance, and Z_g the pipe grounding impedance of the GI bus which consists of resistance $R_g=5\Omega$ and inductance $L_g=3\mu H$ of the pipe grounding wire. The GI bus length is taken as 50m. The GI bus parameters are calculated using the EMTP Cable Constants at frequency f=1kHz considering the steady-state power frequency. The first phase (phase-a) of the circuit breaker CB is closed at t=0 corresponding to the phase-a peak voltage of a 3-phase cosine ac source. As well-known, a non-simultaneous closing of a 3-phase CB produces a higher overvoltage than that in the 3-pahase simultaneous closing case. The effect of the non-

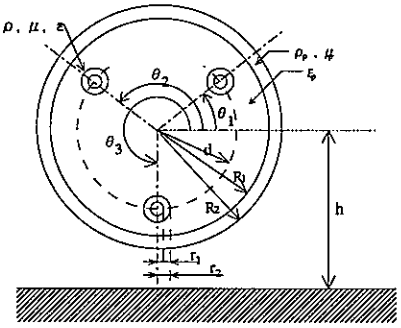


Fig 1 Cross-section of a gas-insulated bus

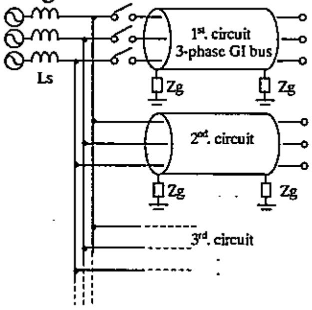


Fig. 2 A model circuit of basic investigation

simultaneous CB closing needs to be investigated. The following closing duration is considered.

case 1 : 3-phase simultaneous closing at t=0
case 2 : phase-a closed at t=0, phase-b at 6.667ms, phase-c at 3.333ms
case 3 : phase-a at t=0, b at 13.33ms, c at 6.667ms
case 4 : phase-a at t=0, b at 1.0ms, c at 2.0ms
case 5 : phase-a at t=0, b at 2.0ms, c at 1.0ms

3. Basic Investigation

3.1 Effect of the number of parallel circuits

Fig. 3 shows a calculated result of a switching surge when the 3-phase CB in Fig. 2 are closed simultaneously to a single-circuit 275kV GI bus. The phase-a core voltage shows a typical closing surge waveform. The pipe voltage is negligibly small. Fig. 4 shows a switching surge when one circuit (2nd circuit) is connected to the main bus in Fig. 2, and the CB is closed to the other single circuit (1st circuit). The fundamental oscillating frequency becomes lower corresponding to the total bus length becoming greater. The pipe voltage reaches 24.8kV (0.110pu) which is far greater than that in Fig. 3 where no circuit is connected to the main bus.

Fig. 5 gives the maximum overvoltage on the energized (closed) circuit as a function of the number of GI bus circuits connected to the main bus. The core voltages tend to decrease and the pipe voltages increase as the number of the circuits increases. Finally, the both voltages become constant. The pipe voltage shows the greatest overvoltage of about 92kV (0.410pu) in the simultaneous closing (case 1) of the 3-phase CB. No significant difference is observed between the maximum overvoltages at the sending and receiving ends of the pipe.

A 154kV gas-insulated bus shows a similar tendency of the pipe overvoltages to those in the 275kV case.

3.2 Effect of CB closing sequence

Fig. 6 shows the effect of the non-simultaneous CB closing. Case 3 of the non-simultaneous closing is observed to produce the largest pipe overvoltage. Fig. 5 shows the maximum pipe overvoltage in case 3 as a function of the number of parallel circuits. A similar trend to the simultaneous closing case is observed, but the greatest overvoltage reaches 208kV (0.926pu) which is more than double of that in the simultaneous closing case.

The pipe overvoltage may break down the air insulation of the pipe of a 275kV gas-insulated bus.

3.3 Effect of pipe grounding condition

There exist various grounding conditions of the pipe of a GI bus depending on a utility company. Fig. 7 illustrates

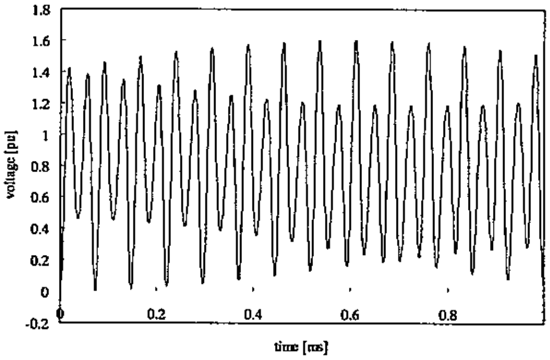


Fig. 3 Switching surge on phase-a in a single-circuit

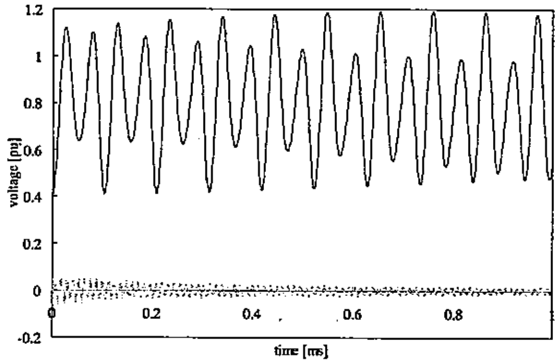


Fig. 4 Switching surge on energised phase-a in a double-circuit

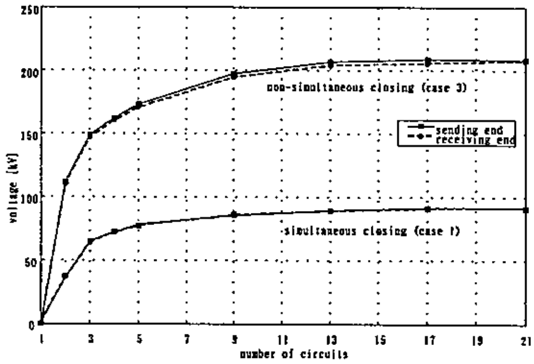


Fig.5 Maximum pipe overvoltage at energized circuit

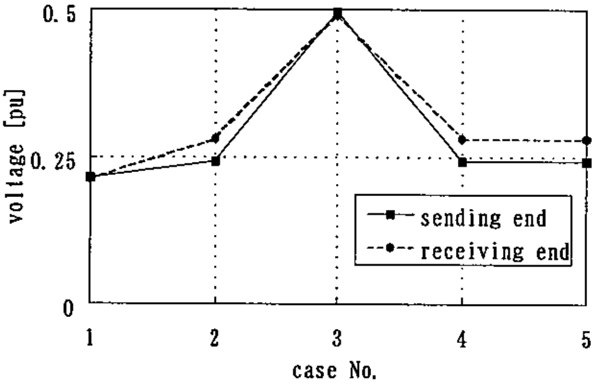


Fig.6 Effect of CB closing sequence

the grounding conditions of the pipe, where the V-I characteristic of a pipe protecting arrester is taken from Reference (4). The corresponding transient voltage waveforms at the pipe center are shown in Fig. 8. Table 1 summarizes the maximum overvoltages. The pipe overvoltage is highly dependent on the pipe grounding conditions as observed in Table 1. The overvoltage is decreased largely by the grounding of the both ends of the pipe (case d). Therefore, the arrester installed at the center of the pipe shows a minor effect of the overvoltage control. When one terminal of the pipe is grounded, the overvoltage at the other end is controlled to be half by the arrester, but the overvoltages are still large. This is the same when the arresters are installed at the both ends of the pipe. Thus, the both ends of the pipe should be grounded as far as it is possible. The reason for such a high overvoltage even with an arrester is estimated to be caused by the grounding wire inductance of the arrester. Case a" to d" in Table 1 shows the pipe overvoltage when the inductance is neglected. It is clear that the overvoltages becomes smaller than those in case a' to d' except that at the pipe center. Thus, the grounding wire should be taken as short as possible.

4. Overvoltages in A Gas-Insulated Substation

It has been made clear that a large pipe overvoltage appears if a number of GI buses are connected to a main bus. Such a situation can be often observed in a gas-insulated substation. Thus, switching overvoltages due to disconnecting switch (DS) operation are investigated in this chapter.

4.1 Substation model

Fig. 9 illustrate a model circuit of a 154kV gas-insulated substation of which a cross-section of the gas-insulated bus is given in Fig. 1. In Fig. 9, a 3-phase ac voltage source is applied to node PWO through 20mH source inductance , and LA is an arrester of which the V-I characteristic is taken from Reference (4). A pipe grounding resistance is 5Ω and the grounding wire is represented by a lumped inductance of 3μH. Disconnectors DS1 and DS2 are installed between nodes BU-05 and BU-06, and between BU-06 and B2-06 respectively as illustrated in Fig. 9

4.2 Effect of DS closing sequence

The effect of non-simultaneous DS2 closing will be investigated, where DS1 is deadly closed. The closing durations are the same as those in Sec. 3.2.

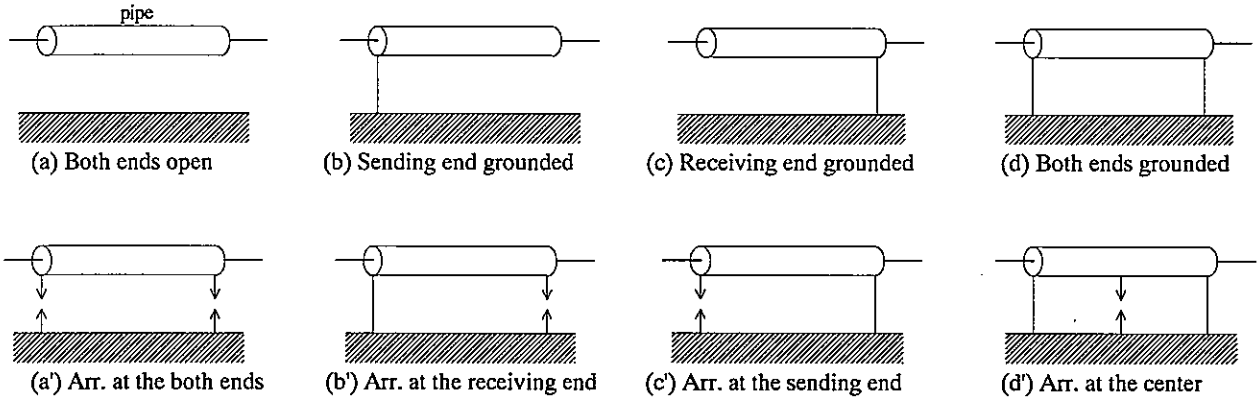
Pipe maximum voltages at nodeTR-01, the entrance of a transformer, in Fig. 9 are :

case 1 : -0.213, case 2 : -0.105, case 3 : -0.227,
case 4 : 0.111, case 5 : 0.202 [pu]

It is observed in the above that case 3 generates the highest pipe overvoltage among the investigated closing sequence. The overvoltage is nearly the same as that in the simultaneous closing (case 1). This is quite different from the observation made in a simple gas-insulated bus system in Sec. 3.2. The reason for this is estimated that the highest overvoltage is generated by multiple reflections and refractions of traveling waves within the complex

Table 1 Maximum pipe overvoltages

case	maximum overvoltage [pu]		
	sending end	center	receiving end
a	-0.690	-0.833	-0.966
b	-0.172	0.628	-0.931
c	-0.770	-0.779	-0.241
d	0.188	-0.274	-0.202
a'	-0.253	-0.356	-0.381
b'	-0.172	-0.444	-0.347
c'	0.330	0.450	-0.378
d'	0.185	-0.253	-0.198
a"	-0.244	-0.322	-0.316
b"	-0.172	-0.443	-0.261
c"	0.263	0.459	-0.377
d"	0.185	-0.240	-0.198



(a) Both ends open (b) Sending end grounded (c) Receiving end grounded (d) Both ends grounded

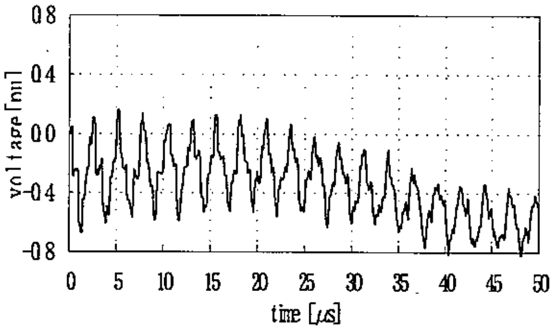
(a') Arr. at the both ends (b') Arr. at the receiving end (c') Arr. at the sending end (d') Arr. at the center

Fig.. 7 Grounding conditions of the pipe connection of the GI bus in the substation.

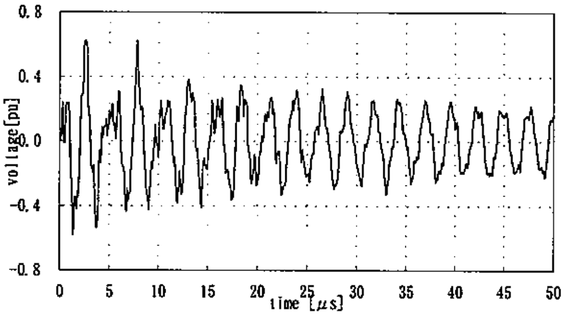
For a simplicity and considering the above, the simultaneous closing is adopted as the DS operation in the following investigation.

4.3 Effect of connecting buses

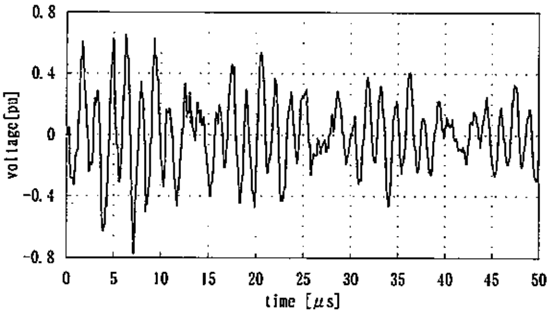
The effect of bus connection explained in Table 2 on a



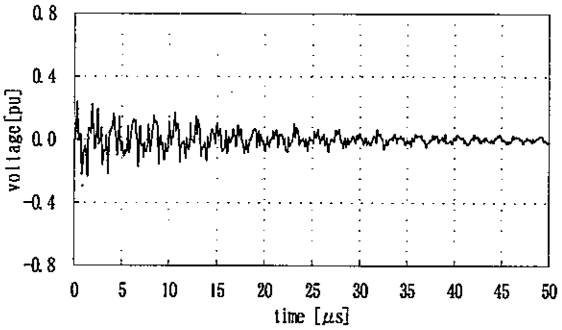
(a) Both ends open



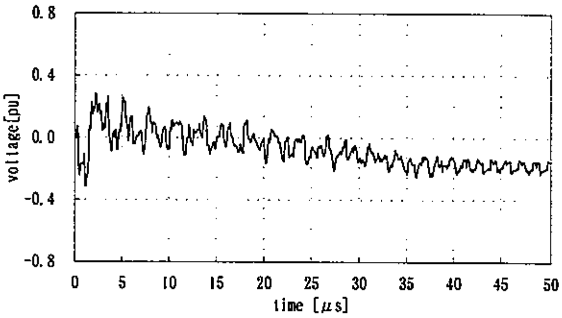
(b) Sending end grounded



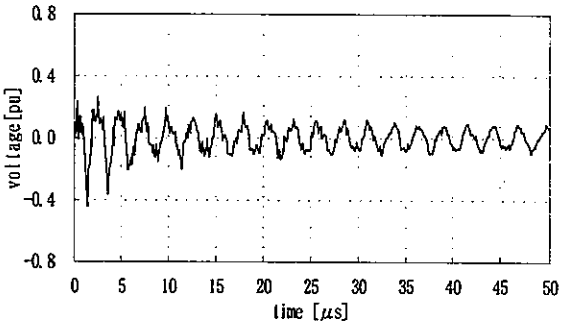
(c) Receiving end grounded



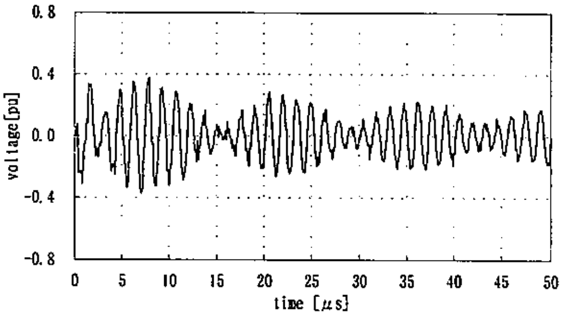
(d) Both ends grounded



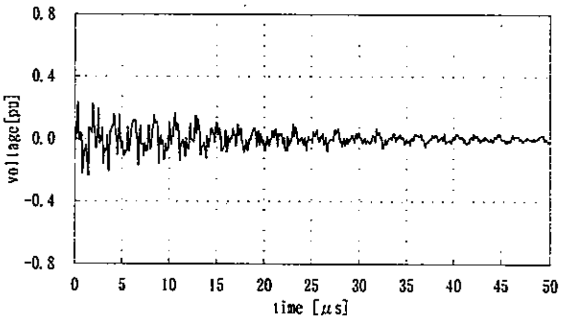
(a') Arr. at the both ends



(b') Arr. at the receiving end



(c') Arr. at the sending end



(d') Arr. at the center

Fig. 8 Effect of pipe grounding condition pipe overvoltage is investigated. The pipe of the bus is connected to the outer conductor of the DS because this condition generates a higher overvoltage. Calculated results of the pipe overvoltages at the transformer entrance are included in the table.

In the case of no bus connected to the DS1 bus except buses B2-06 to B2-02 to the transformer (case 1), the pipe overvoltage at the transformer entrance (node TR-01) is observed to be 0.208pu. The overvoltage is increased to 0.265pu in case 2 by connecting bus B2-05 - B2-07 at node B2-05. The increase is estimated to be caused by successive reflections of traveling waves at the open-circuited node B2-07. The overvoltage is decreased to 0.135pu in case 3 by connecting buses at node BU-06 to the right. This is reasonable because the surge impedance seen from node BU-06 to the right becomes lower by connecting the buses at node BU-06. The observation corresponds to that made in Sec. 3.1, i.e. the lower the source-side impedance at the CB bus, the higher the pipe overvoltage. Namely in case 3, the source-side impedance becomes higher in comparison with the load-side impedance, and thus the overvoltage becomes lower. The above is the cases of DS1 operation.

In cases 4 to 15, DS1 is deadly closed and DS2 is operated. In case 4, where buses BUS1, BUS2 and BUS3 are not connected to the DS2 bus, the pipe overvoltage at the transformer entrance is 0.273pu. When BUS1 is connected to the DS2 bus (source side) in cases 5, 6 and 9, the source side impedance becomes lower and correspondingly the pipe overvoltage is increased. The increase is greater when the length of the BUS1 is smaller (case 5). But the degree of the increase is small, and saturates by the BUS1 length of 10m as observed in cases 6 and 9. A comparison of overvoltages between cases 6 to 8 makes it clear that the greater the number of buses connected to the source side of the DS2 bus, the higher the pipe overvoltage.

The effect of buses (BUS2) connected to the load side of the DS2 bus is investigated from cases 10 to 14 and case 4. It is clear that the pipe overvoltage becomes lower as the number of buses connected to the DS2 load side becomes greater. The degree of the decrease is smaller as the connected bus length becomes longer. The effect of BUS3 connected at node B2-05 is similar to that of BUS2, but the overvoltage decrease is small.

The above observation corresponds to that in Sec. 3.1.

It is concluded that the lower the source-side impedance of

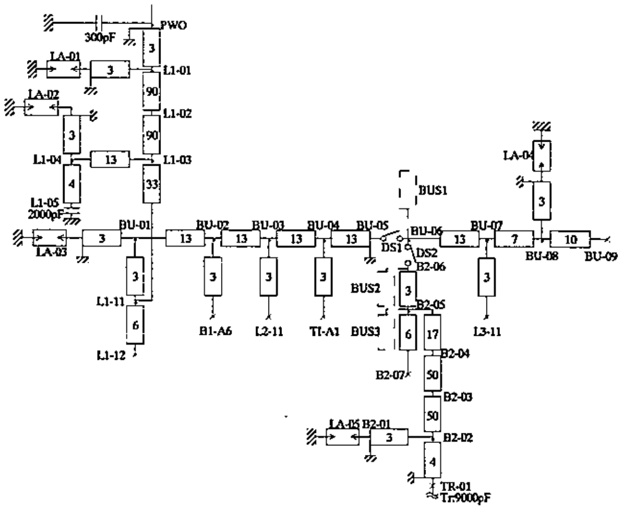


Fig. 9 Model of a gas-insulated substation

Table 2 Calculation condition and results

(1pu=125.74kV)

case	DS1	DS2	BU-06 to the right	B2-05–B2-07	BUS1	BUS2	BUS3	max. overvoltage [pu]
1	closing	○	–	–	–	–	–	0.208
2	closing	○	–	○	–	–	–	0.265
3	closing	○	○	○	–	–	–	0.135
4	○	closing	○	○	–	–	–	0.273
5	○	closing	○	○	3m×1	–	–	0.312
6	○	closing	○	○	10m×1	–	–	0.305
7	○	closing	○	○	10m×2	–	–	-0.390
8	○	closing	○	○	10m×5	–	–	-0.530
9	○	closing	○	○	50m×1	–	–	0.305
10	○	closing	○	○	–	3m×1	–	0.165
11	○	closing	○	○	–	3m×2	–	0.149
12	○	closing	○	○	–	3m×3	–	0.142
13	○	closing	○	○	–	10m×1	–	0.173
14	○	closing	○	○	–	50m×1	–	0.206
15	○	closing	○	○	–	–	6m×1	0.242

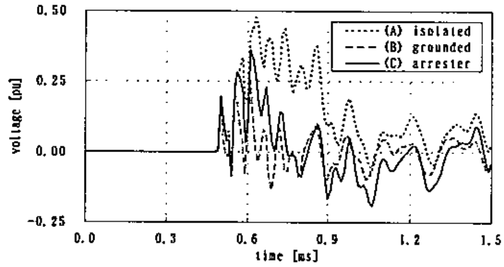
○ deadly closed – open

a CB or DS bus compared with the load-side impedance, the higher the pipe overvoltage due to the CB or DS operation.

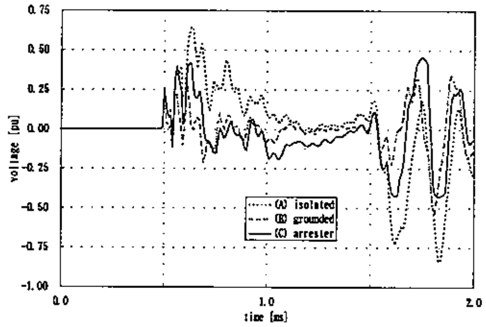
4.4 Effect of pipe protection arrester

The effect of a pipe arrester (limiting voltage 45kV) on a pipe overvoltage due to the disconnector DS2 is investigated in the following conditions.

case A : nodes TR-01 and B2-01 isolated from the earth
case B : nodes TR-01 and B2-01 grounded with resistance 5Ω and inductance 3μH of grounding wire
case C : arresters installed at nodes TR-01 and node B2-01 same as case B



(a) Case 4



(b) Case 8

Fig. 10 Effect of the arrester

Table 3 Effect of arrester on pipe overvoltage (1pu=125.74kV)

Condition of the pipe of node TR-01	maximum voltage [pu]	
	case 4	case 8
(A) isolated	0.481	-0.845
(B) grounded	0.273	-0.530
(C) arrester	0.371	0.571

The voltage waveform at node TR-01 of the pipe is shown in Fig. 10 for the cases 4 and 8 in Table 2 which generate the highest overvoltage with no arrester. The maximum overvoltages at node TR-01 are given in Table 3. It is clear that the pipe overvoltage is the lowest when the both nodes are grounded (case B). The arrester at node TR-01 (case C) decreases the overvoltage, but it is greater than that in case B Therefore, the pipe of a gas-insulated bus in a substation should be grounded as far as it is possible, and the pipe arrester may be installed at an open-circuited terminal of the pipe.

5. Conclusions

The paper has investigated switching overvoltages on pipes of gas-insulated buses in a gas-insulated substation. The following conclusions have been obtained based on the investigation.

(1)The switching surge overvoltage on the pipe due to CB or DS closing increases as the number of the buses connected to the source side increases, and the overvoltage decreases as the number of the buses connected to the load side increases.

(2)In a gas-insulated bus, the switching overvoltage significantly depends on a pipe grounding condition. An arrester installed to the pipe is effective to reduce the pipe overvoltage but the overall voltages may not be sufficiently controlled to less than the pipe insulation level. Thus, pipe protection has to be co-ordinated with its grounding.

(3)The high switching overvoltage on the pipe is partially but strongly affected by the inductance of the grounding wires of the pipe and the arrester. Therefore, the grounding wire length has to be taken as short as possible.

References

1) CIGRE WG13-05: "The calculation of switching surges, Part III", ELECTRA, Vol. 62, pp. 45-78, 1979. 1
2) Ametani, N. Nagaoka & K. Shimizu: "Switching overvoltages on sheath in multicircuit cable system", ICEE '96 Proceedings, Vol. 2, pp. 769-773, 1996. 8.
3) W. Scott-Meyer: ATP Rule Book, B.P.A., 1994.
4) "ZnO arrester of Meidensha", Meidensha Catalogue GP-HA-10290D, 1992.