IEEE Access
Multidisciplinary Rapid Review Open Access Journal

Received March 1, 2017, accepted March 28, 2017, date of publication April 18, 2017, date of current version May 17, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2695490

Transient Electromagnetic Disturbance Induced on the Ports of Intelligent Component of Electronic Instrument Transformer Due to Switching Operations in 500 kV GIS Substations

HENG-TIAN WU[1], CHONG-QING JIAO[1], XIANG CUI[1], (Senior Member, IEEE), XIAO-FAN LIU[2], AND JIAN-FEI JI[3]

[1]School of Electrical Engineering, North China Electric Power University, Beijing 102206, China
[2]State Grid Jiangsu Economic Research Institue, Nanjing 210000, China
[3]Sate Grid Jiangsu Electric Power Company Research Institute, Nanjing 210000, China

Corresponding author: Heng-Tian Wu (emc20150304@outlook.com)

ABSTRACT Switching operations in gas-insulated switchgear (GIS) substations generate transient electromagnetic fields in the GIS pipes. These fields leak out discontinuities of the GIS and induce electromagnetic disturbance voltages on the cables and ports of secondary circuits. In smart GIS substations, secondary devices especially, such as the intelligent component of electronic instrument transformer, are vulnerable to electromagnetic interference. In this paper, the disturbance voltages induced on the ports of intelligent component of electronic instrument transformer had been measured in three 500-kV GIS substations, respectively. The disturbance was generated either during disconnector (DS) switching operations or circuit breaker (CB) operations. Then, the time-domain and frequency-domain characteristics of the disturbance waveforms have been analyzed. The micro-pulses of disturbance voltages have been extracted from the raw data. The waveform parameters, including peak voltage, rise-time, dominated frequency, and duration, have been calculated by the statistical analysis. The comparison between disturbance during DS switching operations and that of CB operations has been made. Also, the differences and similarities of disturbances between the three GIS substations have been displayed. Furthermore, the differences between measured waveforms and the IEC 61000-4-18 immunity test standard waveform have been discussed.

INDEX TERMS Electromagnetic interference (EMI), gas-insulated switchgear (GIS), DS switching operation, CB switching operation, electronic instrument transformer, intelligent component, port disturbance voltages, transient voltages measurement.

I. INTRODUCTION

Gas-insulated substation (GIS) has been widely used in the power delivery of 110 kV, 220 kV, 330 kV, 500 kV, 750 kV and 1000 kV today. With the information techniques and relay protection developed continually, more upgraded electronic devices are employed by the smart GIS substations [1]–[3]. These devices for measuring and monitoring, such as electronic instrument transformers, merging units, intelligent terminals, are fixed on the gas-insulated switchgear pipe or enclosed in the local control cabinet. These devices are vulnerable to the electromagnetic interference (EMI). Usually, the control cabinet is placed in the switchyard close to the disconnectors (DS) and circuit breakers (CB). The sensors for measuring or protection, such as electronic instrument transformers, are connected by cables to the intelligent component (merging units and intelligent terminals) inside the control cabinet. During the switching operations, very fast transient over-voltages (VFTOs) generated in the GIS pipe [4]–[6]. These transients leak out discontinuities of GIS pipe like bushings or basin insulators, and then interfere with the nearby cables. On the ports of intelligent component that connected to cables, transient disturbance voltages are induced. Sometimes, the disturbance is so serious that it will cause the failure of intelligent components [7]–[9].

Many experiments had been carried out to research the transient phenomena induced on secondary circuits during switching operation in substations. C. M. Wiggins *et al.* measured the voltages and currents induced on the CT control cables caused by switching operation in 500 kV AIS/GIS substations and used the circuit model to simulate the disturbance [10], [11]. M. M. Rao *et al.* measured the voltages induced on CT circuits and analyzed the spectra.

Then, the influence of different cable length had been discussed [12], [13]. EPRI also carried out a series of experiments and statistically analyzed the electromagnetic interference (EMI) levels on sensitive electronic equipment in air/gas insulated substations of different voltages due to switching operations [14], [15]. However, the above results were concluded from the conventional substations. The layout of secondary devices in smart GIS substations differs from that in conventional substations greatly. In a smart substation, the intelligent component is placed close to the switchgear. In a conventional substation, most secondary equipment is located in the relay protection rooms, which are far away from the DS and CB. The primary and secondary equipment are connected by cables with a length of up to 100 meters. Due to the difference between smart substations and conventional substations in the layout, the transient disturbance characteristics induced on secondary circuits of smart substations may differ from the results presented in the above references. By comparison, the research on electromagnetic disturbance of intelligent component ports in smart GIS substations has been scarcely reported so far. Hence, it is necessary to carry out experiments on this issue.

Additionally, the reliable simulation of electromagnetic disturbance is very difficult for a realistic substation due to the complex structure and environment. In contrast, the onsite measurement of the disturbance voltages on the ports is an intuitive and effective approach to master the level and characteristics of the disturbance. The results have significant importance to research and develop protection techniques against EMI. Also, the data help to enact the immunity requirements and mitigation guidelines. As the typical measuring and monitoring secondary electronic devices, electronic instrument transformers get many advantages such as fast frequency response, simple insulation design and without magnetic saturation problem. However, electronic instrument transformers are not reliable enough with high fault rate in practices due to EMI problems, which is an urgent issue to be solved [16], [17]. In this paper, the tests aimed at transient electromagnetic disturbance voltages induced on the ports of the intelligent component of electronic instrument transformers have been carried out in three smart 500 kV GIS substations. Then, the disturbance voltages level, the time-domain waveform characteristics and the spectra are extracted and summarized.

This paper is organized as follows. Section II introduces the experiment configuration in 500 kV GIS substations and the measurement system. Section III describes the test contents in each GIS substation. Also the corresponding characteristics from raw data are investigated. Furthermore, the measured waveform characteristics are compared with those described in IEC61000-4-18 [18] in this section. Finally, this paper is summarized in Section IV.

II. EXPERIMENT CONFIGURATION

The electronic instrument transformers capable of measuring and monitoring the voltage/current of primary circuits, have been used gradually in 500 kV smart substations. As Fig.1 shows, the electronic instrument transformer is fixed on the GIS pipe. High voltage and large current of the primary circuit are attenuated by it and then become voltage/current signals. These signals are transmitted through cables to the intelligent component inside the control cabinet for further digital processing. Next these digital signals are transformed to optical signals in the local control cabinet and finally transmitted to the relay rooms far away through fibers. Usually, the cable coming out of the transformer pass through metal bellow to the ground. It is laid underground along tunnels and connected to the control cabinet. According to the specifications of typical design for substations, the shield of the cable is grounded in the control cabinet and floating on the sensor side of the electronic instrument transformer. The intelligent component includes merging unit and intelligent terminal. The ports set on the ports-bar for manual measurement during GIS test or overhaul, are connected with corresponding cable wires.

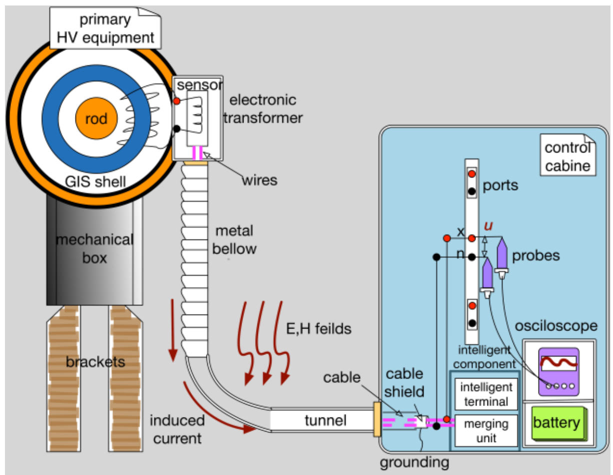


FIGURE 1. The configuration of GIS primary HV equipment and control cabinet.

Considering the transient voltages resulted from DS switching operation can cover a wide frequency range from DC up to 100MHz. The transient spatial electromagnetic field can exceed 30 kV/m and over 100 A/m. The transient enclosure voltage(TEV) of the GIS shell can reach a few tens of kilovolts [19], [20]. Thus in our test, a kind of high-voltage probe PINTECH P6039A is selected, which can measure signals from DC to 220 MHz and bear 40 kV at most. The oscilloscope used in the test is YOKOGAWA-DLM2000 and its sample time is set to be 1.6 ns. The probes together with the oscilloscope is placed inside the metal boxes with 40 dB shielding effectiveness, which forms a measurement system with ±40 kV voltage range and 125 MS per channel onboard memory. The oscilloscope is powered by the battery as shown in Fig.1 and is remotely controlled by a computer connected to the oscilloscope by an optical fiber. During the tests, the whole system is placed in the control cabinet to avoid interference by the electromagnetic fields. With fiber communication, separated power supplying and shielding box, this measurement system gets an excellent quality of anti-EMI, which had been used in several 500 kV GIS substations and the 1000 kV GIS test circuit [20]–[22].

III. TEST CONTENTS AND ANALYSIS

A. SUBSTATION #1

The circuit layout of 500 kV GIS substation #1 is shown in Fig.2. The disturbance voltage in the control cabinet of electronic instrument transformer #5061CT1 is measured at position M1 close to the CB #5061 and that of #5062CT1 is measured at position M2 close to the CB #5062.

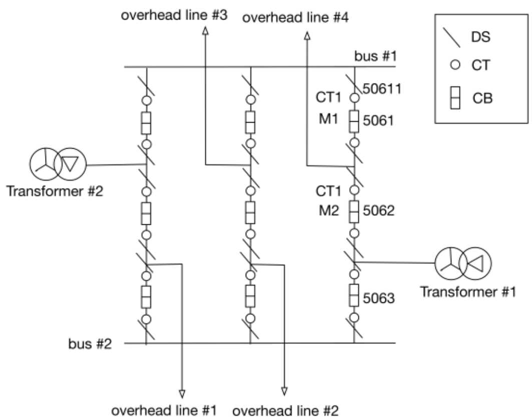


FIGURE 2. The circuit layout of 500 kV GIS substation #1.

1) DS OPERATION

In the test, bus #1 was charged by transformers. CB #5061 was kept open. The DS #50611 was closed and opened three times respectively. The port disturbance voltages of #5061CT1 and #5062CT1 were measured. As shown in Fig.1, at each port, two voltages are measured. One named "u_x" represents the voltage between one of the phase lines (A, B, or C) and the ground in control cabinet. The other one "u_n" is the neutral line voltage to the ground. The common-mode (CM) voltage u_c is calculated as Eq.1 and the differential-mode (DM) voltage u_d is calculated as Eq.2.

$$u_c = (u_x + u_n)/2 \quad (1)$$

$$u_d = (u_x - u_n)/2 \quad (2)$$

The voltage u_x, u_n measured in the test from #5061CT1 and #5062CT1 are shown in Fig. 3 and Fig.4 respectively. The full waveform is a burst including a series of micro-pulses caused by a number of prestrikes and restrikes during the closing/opening operations of the DS. Fig. 3(a) and 3(b) show the waveform of u_x for opening operation and closing operation respectively. Likewise, Fig.3(c) and 3(d) correspond to u_n. The typical full waveform (full-wave) lasts hundreds of milliseconds and it consists of hundreds of micro-pulses with different peaks. For the closing operation, the first micro-pulse is the max and the following pulses are becoming smaller. For the opening operation, the peak of micro-pulses has an opposite evolution tendency to that of the closing operation. Fig.5 shows typical micro-pulses extracted from full time-domain waveforms of voltage u_x of two CTs. The micro-pulse waveform is a damped oscillatory waveform and it lasts several microseconds. Fig.6 shows the spectra. The spectra of #5062CT1 have more high frequencies around 30MHz, than those of #5061CT1. The dominated frequencies range from 0.3MHz to about 20MHz. No matter for #5061CT1 or #5062CT1, the u_x and u_n have similar spectra.

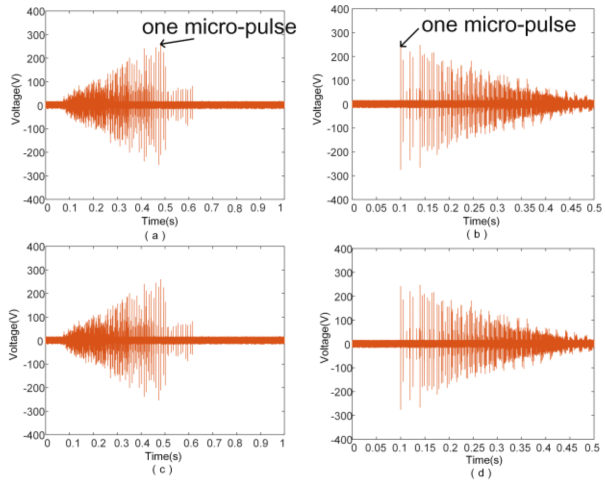


FIGURE 3. The full time-dome waveforms of disturbance voltages from #5061CT1: (a) u_x, opening operation. (b) u_x, closing operation. (c) u_n, opening operation. (d) u_n, closing operation.

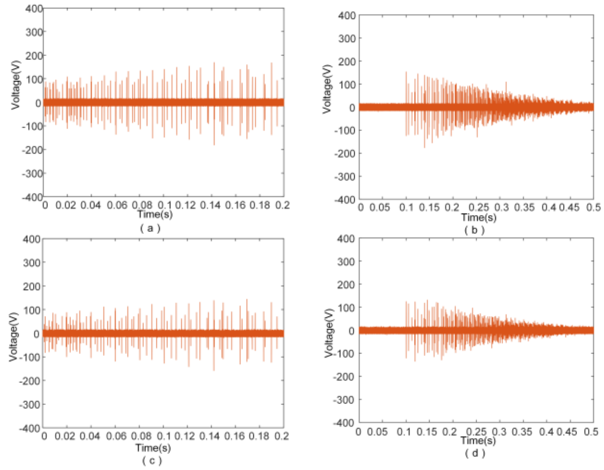


FIGURE 4. The full time-dome waveforms of disturbance voltages from #5062CT1: (a) u_x, opening operation. (b) u_x, closing operation. (c) u_n, opening operation. (d) u_n, closing operation.

Actually, the IEC 61000-4-18 standard recommends a standard damped oscillatory waveform for the immunity test of secondary devices, which especially relates to the immunity test for electric equipment, under operational conditions, with regard to repetitive damped oscillatory waves occurring

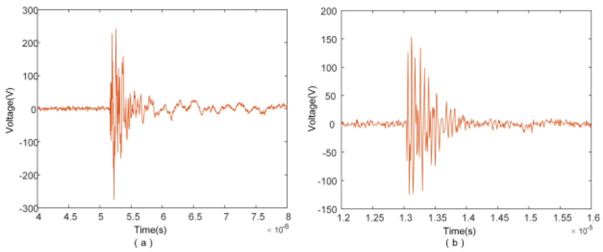


FIGURE 5. The micro-pulses: (a) u_x, #5061CT1; (b) u_x, #5062CT1.

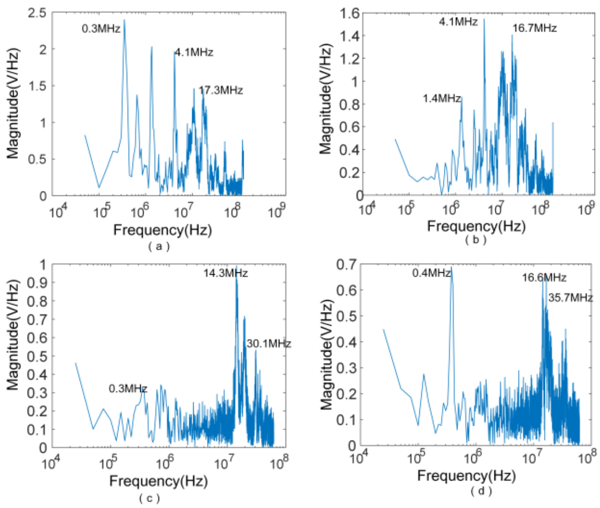


FIGURE 6. The micro-pulses spectra: (a) u_x, #5061CT1; (b) u_n, #5061CT1; (c) u_x, #5062CT1; (d) u_n, #5062CT1.

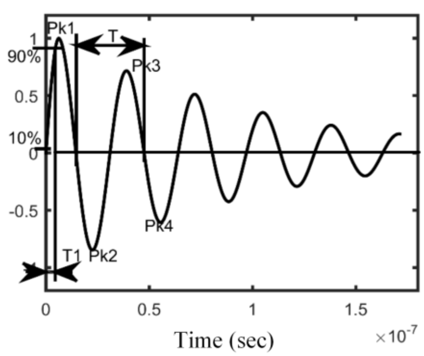


FIGURE 7. Waveform definition form IEC of the damped oscillatory wave.

mainly in power, control and signal cables installed in GIS. According to it, the preferential range of test levels for the damped oscillatory wave test: the 1st level is 0.5 kV, the 2nd level is 1 kV, the 3rd level is 2 kV and the 4th level is 4 kV. At last, the X level is customized according to practical situation. The test level is defined as the voltage of the first peak (Pk1čmaximum or minimum) in the waveform as Fig. 7 shows.

In the waveform T_1 is the rise-time, which is the time taken by the voltage to change from the 10% of the first peak to the 90% of this peak. The oscillation frequency is the defined as

TABLE 1. The Parameters of damped oscillatory wave.

Oscillatory frequency(MHz)	3	10	30
Repeat rate(Hz)	5000	5000	5000
Peak(V)	4/2/1/0.5	4/2/1/0.5	4/2/1/0.5
Full-wave duration(ms)	50 (1±20%)	15 (1±20%)	5 (1±20%)
Micro-pulse counts	250	75	25
Micro-pulse duration(μs)	3.33	1	0.33
Rise-time(ns)	5(1±30%)	5(1±30%)	5(1±30%)

TABLE 2. The statistics of the port disturbance voltages from #5061CT1 and #5062CT1.

	#5061CT1(close/open)			
	u_x	u_n	u_c	u_d
Peak(V)	286.2/294.3	265.4/277.4	206.8/217.4	110.2/116.5
Full-wave duration(ms)	395.7/540.4	437.2/540.5	394.3/540.5	340.2/506.8
Micro-pulse counts	374/326	376/338	337/317	187/219
Rise-time(ns)	12/14	16/16	12/16	4/8
Micro-pulse duration(μs)	11.4/18.7	6.7/7.7	14.3/24.7	12.6/12.8
	#5062CT1(close/open)			
	u_x	u_n	u_c	u_d
Peak(V)	159.4/175.9	178.5/201.8	156.3/165.8	62.7/71.3
Full-wave duration(ms)	390.9/-	359.6/504.4	359.6/-	300.2/-
Micro-pulse counts	314/-	253/286	259/-	97/-
Rise-time(ns)	16/10	24/19.2	16/16	16/13
Micro-pulse duration(μs)	5.8/7.0	3.8/5.1	6.6/5.3	13.0/7.8

the reciprocal of the period T that is the time between the first and third crossing after the initial peak. The following Table 1 lists the parameters of the waveform. Wherein, repeat rate=micro-pulse counts/full-wave duration.

For further analysis and mastering the disturbance characteristics, referring to the standard, the parameters have been extracted from the raw data and the statistics are listed in Table 2. Overall, more than seven thousand micro-pulses have been extracted from the raw data. The peak is the statistics of the max and the other items are the means. For example, the number 286.2 at line 3 column 2 is the max of all micro-pulses peaks of u_x from #5061CT1 during closing operation. The number 395.7 at line 4 column 2 is the mean of full-wave duration of all u_x full waveforms from #5061CT1 during closing operation. The data from closing operation and opening operation are separated by the symbol "/". The symbol "−" represents that the data were not captured effectively in the test.

In the table, the max peak is 294.3 V, lower than the 1st level 0.5 kV. The disturbance voltages under two different operations(close/open) have peaks very close to each other(286.2/294.3 V). The peak of #5061CT1(286.2/294.3 V) is higher than that of #5062CT1(159.4/175.9 V) because

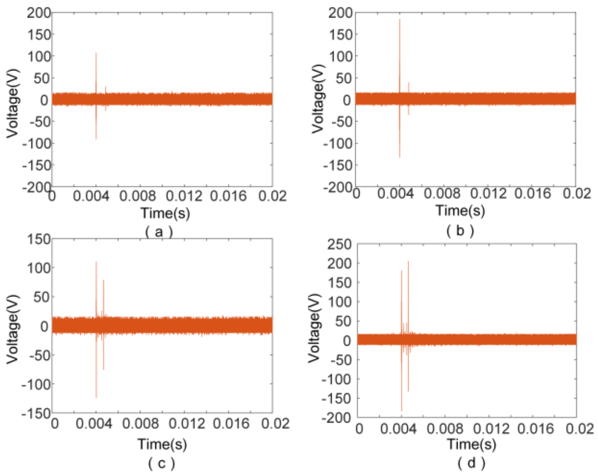


FIGURE 8. The full waveforms disturbance voltages of u_x, u_n during the CB operations: (a). u_x, #5061 operation; (b). u_n #5061 operation; (c). u_x, #5062 operation; (b). u_n #5062 operation.

#5061CT1 is closer to the operated DS #50611 as that Fig.2 shows. The full-wave lasts about 300∼500 ms and one full-wave consists of more than 300 micro-pulses. These pulses usually last about 5∼20 μs. The micro-pulses of #5061CT1(6∼20 μs) have a little longer duration than those of #5062CT1(3∼7 μs). However, the rise-times of two CTs are nearly the same, about 10∼20 ns. Besides, all the parameters have little difference between opening and closing operation. By and large, the CM disturbance voltages have higher peaks, more micro-pulses, longer full-wave duration than the DM voltages do.

2) CB OPERATION

In this test, bus #1 was charged by transformers. The DS of 5061 and 5062 were kept closed. The disturbance voltages of the #5062CT1 were measured during the operation of CB #5061 and #5062 respectively. During the open operation, the CB provides a high-pressure blast of gas to help extinct the arc in the chamber, so the strikes seldom happen. Henceč there are little electromagnetic fields leak out of the GIS. During the closing operation, the CB generally rely on the synchronous closing technology instead of gas-blast technology to avoid the surging current. Restrikes may happen during closing operation. Due to the above features of CBs, the disturbance voltages were measured during either the single closing operation or the open-close-open operation. Overall six closing operations and three open-close-open operations were carried out in this test. Due to the waveform similarity between closing and open-close-open operation, following figures display only the results from closing operations. Fig.8 shows the full waveforms of u_x, u_n during CB #5061 and #5061 operations. Fig.9 depicts the micro-pulses extracted fromu_x and u_n respectively during CB #5062 operation. Fig.10 displays the micro-pulses spectra. The dominated frequency is about 0.1 MHz, which is very lower than that of DS operation. The high frequency component such as 17 MHz is a little.

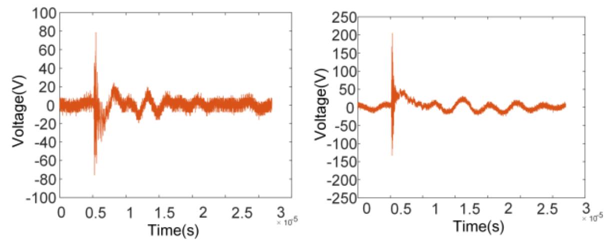


FIGURE 9. The micro-pulses disturbance voltages of u_x, u_n during the CB operations: (a). u_x, #5062 operation; (b). u_n #5062 operation.

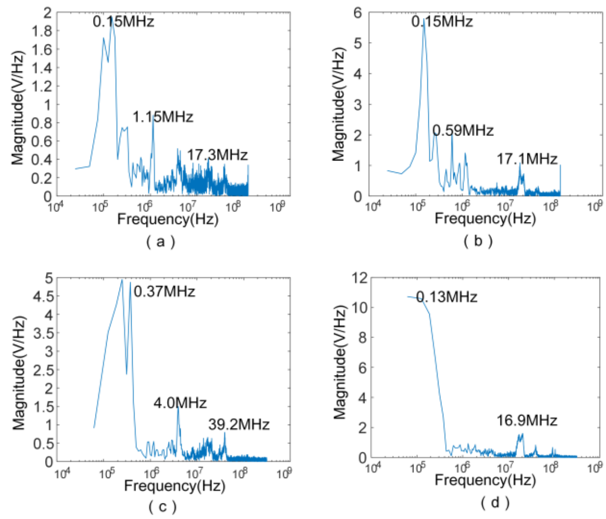


FIGURE 10. The micro-pulses spectra: (a). u_x, #5061 operation; (b). u_n #5061 operation; (c). u_x, #5062 operation; (d). u_n #5062 operation.

Similar to the analysis of DS operation, Table 3 lists the characteristics of these disturbance voltages. The disturbance voltages of open-close-open operation have higher peaks, longer full-wave and micro-pulse duration than those of single closing operation. The CM voltages are higher than DM voltages. The peaks during #5062 operation are a little higher than those during #5061 operation. Also the full-wave and micro-pulse of #5062 operation last longer than those during #5061 operation. These results remind that: if there are two adjacent CBs (e.g. CB.1 and CB,2), the disturbance induced in the local control cabinet connected to one CB.1 during the other adjacent CB.2 operation may be severer than the disturbance in the local control cabinet connected to CB.1 generated during CB.1 operation.

Observing the data of #5062CT1 from Table 2 and Table 3, we find that the disturbance generated during DS operation and CB operation have much differences. For single closing operations, the peak of DS operation is a little higher than that of CB operation. But the peak of CB open-close-open operation(485.5 V) is the highest among all these operation styles. Additionally, due to the faster operating speed of CB, the full-wave of CB operation lasts much shorter and has much less micro-pulses caused by restrikes than those of DS operation. However, in term of micro-pulse duration,

TABLE 3. The statistics of #5062CT1 port disturbance voltages during CB #5061 and #5062 operation.

	#5061(close/open-close-open)			
5062CT1	u_x	u_n	u_c	u_d
Peak(V)	143.9/233.6	226.5/368.4	182.1/300.9	88.7/116.2
Full-wave duration(ms)	0.59/1.82	0.59/1.82	0.59/1.82	0.59/1.82
Micro-pulse counts	2/3	2/3	2/3	2/3
Rise-time(ns)	13.6/13.6	33.2/13.6	32.8/16.0	29.2/20.8
Micro-pulse duration(μs)	9.3/38.3	23.3/38.3	20.8/20.7	26.2/37.8
	#5062(close/open-close-open)			
5062CT1	u_x	u_n	u_c	u_d
Peak(V)	146.4/223.7	303.2/485.5	208.0/326.8	108.4/189.8
Full-wave duration(ms)	2.25/3.30	2.25/3.30	2.25/3.30	2.25/1.20
Micro-pulse counts	3/3	3/3	3/3	3/3
Rise-time(ns)	12.0/14.4	21.6/20.8	23.2/19.2	16.8/16.0
Micro-pulse duration(μs)	31.2/48.1	39.9/54.0	35.7/44.5	36.2/55.0

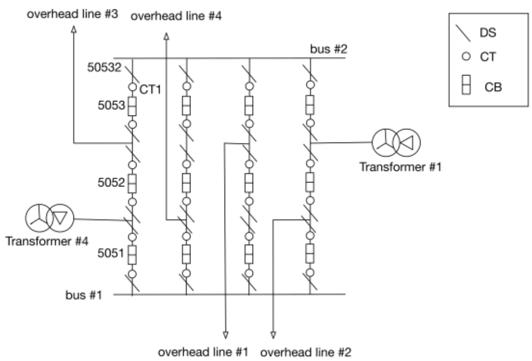


FIGURE 11. The circuit layout of 500 kV GIS substation #2.

CB operation has longer duration than DS operation does. The rise-time of DS operation is a little shorter than that of CB operation. According to the above data, the CB operation may produce larger peaks than DS operation does. Up to now, the disturbance voltages during DS operation are mainly concerned and researched. It seems that the CB operation also needs to be focused on.

B. SUBSTATION #2

In GIS substation #2, only the DS switching operations were tested. As shown in Fig.11, bus #2 was charged by the transformers. We closed and opened the DS #50532 ten times and measured the port disturbance voltages of 5053CT1. Table 4 lists the characteristic parameters.

Though the disturbance time-domain waveforms are similar with those of substation #1, there are still some differences between them. The maximum peak is 482.9 V, higher than the 294.3 V of substation #1 but still lower than the 1st level 0.5 kV. The full-wave durations of closing operation are around 100 ms and those of opening operation are more than 300 ms. They last shorter than those

TABLE 4. The statistics of #5063CT1 port disturbance voltages during DS #50632 operation.

	#5053CT1(close/open)			
	u_x	u_n	u_c	u_d
Peak(V)	482.9/473.1	438.7/419.0	360.4/330.8	200.2/192.9
Full-wave duration(ms)	105.2/317.2	106.6/369.0	106.2/318.6	100.0/307.5
Micro-pulse counts	131/171	139/189	131/183	94/120
Rise-time(ns)	5.1/6.4	3.8/6.4	5.1/6.4	3.8/3.2
Micro-pulse duration(μs)	7.9/8.2	7.3/7.9	8.6/11.8	7.4/7.8

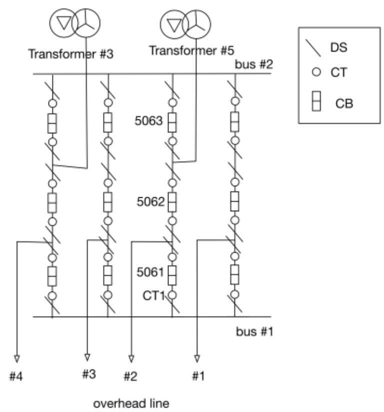


FIGURE 12. The circuit layout of 500 kV GIS substation #3.

(390~540 ms) from substation #1. The full-wave duration of opening operation is longer than that of closing operation, which is also observed from substation #1. A full waveform has about 100~200 micro-pulses, less than the number (253~376) of substation #1. The rise-times are about 5~6 ns, which are shorter than the 10~24 ns of substation #1. The micro-pulses duration is around 8 μs. The dominated frequencies of these disturbances are 1.6 MHz, 8.6 MHz and 10.5 MHz, close to the situation in substation #1.

C. SUBSTATION #3

In GIS substation #3, only the CB switching operations were tested. As shown in Fig.12, bus #1 was charged by the transformers. Three times closing operations and three times open-close-open operations of CB #5061 were carried out. The port disturbance voltages of #5061CT1 were recorded. Table 5 lists the statistics of time-domain parameters.

The peaks in substation #3 are much lower than those measured in substation #1. The max of u_x is just 45.0 V and that of u_n is 85.8 V. Contrary to the situation in substation #1, the peaks during closing operation are a little higher than those generated during open-close-open operation. In terms of time-domain parameters, the full-waves of closing operation last around 1.39~1.46 ms, close to the 0.59~2.25 ms of substation #1. Meanwhile, for the open-close-open operation, they last about 3.5 ms, similar to the 3.3 ms in substation #1. Averagely, the counts of micro-pulses in a full waveform

TABLE 5. The statistics of #5061CT1 port disturbance voltages during CB #5061 operation.

	#5061CT1(close/open-close-open)			
	u_x	u_n	u_c	u_d
Peak(V)	45.0/28.5	85.8/76.1	82.7/68.9	42.3/30.1
Full-wave duration(ms)	1.46/3.52	1.39/3.56	1.36/3.48	1.69/3.62
Micro-pulse counts	3/3	3/3	3/3	3/3
Rise-time(ns)	4.8/6.8	5.6/6.8	5.1/6.4	3.8/3.2
Micro-pulse duration(μs)	0.36/0.61	0.52/0.61	0.62/0.75	0.35/0.80

is 3, which is same with that in substation #1. The rise-time is about 5∼6 ns, shorter than those (12.0∼33.2 ns) of substation #1, but closer to the IEC standard. The micro-pulse duration is very short, less than 1 μs. The dominated frequencies are 0.6 MHz, 3.9 MHz, and 16.7 MHz, similar with the situation in substation #1.

D. DISCUSSION

According to the above tests and statistical analysis, the port disturbance voltages of three different GIS substations are distinct from each other. For the peaks, substation #1 has the maximum 485.5 V under CB open-close-open operations situation. For the full waveforms, under DS operations cases, substation #1 has duration about 359∼540 ms, and substation #2 has duration about 105∼369 ms. During CB operations, the duration range of substation #1 is about 0.5∼3.3 ms and that of substation #3 is about 1.4∼3.5 ms. The full waveforms generated by DS operations have much more micro-pulses than those caused by CB operations have. During DS operations, the max of this number reaches 376 counts in substation #1 and 189 counts in substation #2 respectively. While during the CB operations, the number of micro-pulses counts is two or three. The rise-time varies according to different substations. In substation #1, it is about 12∼24 ns during DS operation and 12∼33 ns during CB operation. In substation #2, this number ranges from 3.8 to 6.4 ns during DS operation. In substation #3, the variation is in the range of 4.8 to 6.8 ns, close to the number in substation #2. The micro-pulse duration of substation #1 is about 3.8∼18.7 μs during DS operation shorter than that (9.3∼54 μs) during CB operation. This parameter of substation #2 ranges from 7.3 to 8.2 μs while in substation #3, it is about 0.3∼0.6 μs. The micro-pulse duration changes much between different substations.

Though the three GIS substation have similar circuit layout and the measurement points are all chosen at the CB or DS nearest the no-load bus, the peak values are so different between substations. Following points may be the reasons. First, the DS and CB used in the three substations have different features such as operating speed, gap capacitor, arc-suppress mechanism and so on. These items directly affect the process of arc striking and further affect the formation of the EM fields in the GIS. Second, the EM fields leak out of bushing at the terminal of GIS coupling to the overhead line and the GIS shell. The coupling degree depends on the wave impendences of overhead line and GIS shell. Third, the metal bellow of cable and the grounding mesh constitute a loop under the GIS. The induced voltages and currents generated in the loop by the leak-out transient fields that propagate along the GIS shell. The size, shape and layout of the loop affect the voltages and currents much. Hence, different length of the cable and the grounding mesh structure make the disturbance different. Last, the port disturbance voltages induced by the loop voltages and currents coupling to the inner wires of the cable through the transfer impedance and transfer admittance of the cable shields. Different cable shields with different transfer impedances/admittances make peaks values different. The structure of the inner wires could also be an influence on the peaks.

The results with DS open/close operation are different from the results with CB open/close operation. This is because the features are different between CB and DS. First, the operating speed has a great effect on the characteristics of the striking process, such as amplitude distribution and striking numbers. The operating speed of CB is much faster than that of DS. So the full waveform during CB operation has fewer micro-pulses than the full waveform during DS operation has. Besides, the CB are designed to interrupt large current in the loop. The DS are designed to isolate the voltage. Hence, the structure of CB is designed quite different from the structure of DS. The VFTOs generated inside the GIS during the striking process is affected by the structure greatly. So the induced port disturbance voltages of DS and CB are quite different from each other.

Moreover, there are some differences between measured disturbance in GIS substations and the referential damped oscillatory waveform of the IEC standard. In reality, the disturbance in GIS substations sometimes last 540 ms much longer than 50 ms. The full waveform have at most 376 micro-pulses, more than 250 micro-pulses supposed by standard. The micro-pulses mostly have longer duration than the ideal referential damped oscillatory waveform. In substation #1, the rise-time of measured disturbance is longer than the reference value 5(1±30%) ns. The disturbance voltages have lower frequency, around 0.3 MHz, lower than the IEC standard range 3∼30 MHz. In terms of the above parameters, the measured waveforms could not be covered completely by the IEC waveform yet.

IV. CONCLUSIONS

The data of the disturbance voltages induced on the ports of intelligent component of electronic instrument transformers in three 500 kV GIS substations under DS operation and CB operation cases had been measured and analyzed. The conclusions are summarized as follows.

1) All the measured port disturbance voltages in our tests, no matter during DS or CB switching operation, are lower than the 1st test level 0.5 kV referred to IEC61000-4-18. The max of them is 485.5 V occurred in the open-close-open CB operation of substation #1.

2) The characteristics of disturbance of DS operations are much different from those of CB operations. Sometimes, the disturbance of CB operation may be severer in term of the peak. Even for the same type of operation (DS or CB), the disturbance characteristics also change from substation to substation.
3) For the DS switching operations, the time-domain characteristics of disturbance voltages are as follows: hundreds of milliseconds full waveform duration; hundreds of micro-pulse counts per full-wave; a few to dozens of microseconds micro-pulse duration; a few to dozens of nanoseconds rise-time.
4) For the CB switching operations, the time-domain characteristics are as follows: a few milliseconds full waveform duration; a few micro-pulse counts per full-wave; less than 1μs or dozens of microseconds micro-pulse duration; a few to dozens of nanoseconds rise-time.
5) Compared to the IEC61000-4-18 standard, the disturbance voltages during DS operation last much longer with more micro-pulses and slower rise-times. In addition, they have frequency component such as 0.3 MHz lower than 3 MHz. For CB operations, the micro-pulse counts is fewer than the corresponding parameter in IEC standard and sometimes, these micro-pulses last longer. Also the dominated frequency is much lower than 3 MHz, about 0.1 MHz. The characteristic parameters of the disturbance waveforms of GIS substation in practice may not be completely covered by the IEC waveform yet.

REFERENCES

[1] Q. Huang, Y. Song, X. Sun, L. Jiang, and P. W. T. Pong, "Magnetics in smart grid," *IEEE Trans. Magn.*, vol. 50, no. 7, Jul. 2014, Art. no. 0900107.

[2] A. M. Miri and Z. Stojkovic, "Transient electromagnetic phenomena in the secondary circuits of voltage and current transformers in GIS (measurements and calculations)," *IEEE Trans. Power Del.*, vol. 16, no. 4, pp. 571–575, Oct. 2001.

[3] N. Harid, A. C. Bogias, H. Griffiths, S. Robson, and A. Haddad, "A wireless system for monitoring leakage current in electrical substation equipment," *IEEE Access*, vol. 4, pp. 2965–2975, Jun. 2016.

[4] J. Meppelink, K. J. Diederich, K. Feser, and W. R. Pfaff, "Very fast transients in GIS," *IEEE Trans. Power Del.*, vol. 4, no. 1, pp. 223–233, Jan. 1989.

[5] Y. Gongchang, L. Weidong, C. Weijiang, G. Yonggang, and L. Zhibing, "Development of full frequency bandwidth measurement of VFTO in UHV GIS," *IEEE Trans. Power Del.*, vol. 28, no. 4, pp. 2550–2557, Oct. 2013.

[6] W.-J. Chen *et al.*, "Study on the influence of disconnector characteristics on very fast transient overvoltages in 1100-kV gas-insulated switchgear," *IEEE Trans. Power Del.*, vol. 30, no. 4, pp. 2037–2044, Aug. 2015.

[7] A. Tavakoli, A. Gholami, H. Nouri, and M. Negnevitsky, "Comparison between suppressing approaches of very fast transients in gas-insulated substations (GIS)," *IEEE Trans. Power Del.*, vol. 28, no. 1, pp. 303–310, Jan. 2013.

[8] H. J. Sutton, "Transients induced in control cables located in EHV substation," *IEEE Trans. Power App. Syst.*, vol. PAS-89, no. 6, pp. 1069–1081, Jul. 1970.

[9] J. F. Ji, L. H. Wang, Y. B. Yuan, and Q. S. Bu, "Analysis and countermeasure on abnormal Operation of one 110 kV intelligent substation merging unit," (in Chinese), *Trans. China Electrotechn. Soc.*, vol. 30, no. 16, pp. 255–260, Aug. 2015.

[10] C. M. Wiggins, D. E. Thomas, F. S. Nickel, and S. E. Wright, "Transient electromagnetic interference in substations," *IEEE Trans. Power Del.*, vol. 9, no. 4, pp. 1869–1884, Oct. 1994.

[11] D. E. Thomas, C. M. Wiggins, T. M. Salas, F. S. Nickle, and S. E. Wright, "Induced transients in substation cables: Measurements and models," *IEEE Trans. Power Del.*, vol. 9, no. 4, pp. 1861–1868, Oct. 1994.

[12] M. M. Rao, M. J. Thomas, and B. P. Singh, "Transients induced on control cables and secondary circuit of instrument transformers in a GIS during switching operations," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1505–1513, Jul. 2007.

[13] M. M. Rao, M. J. Thomas, and B. P. Singh, "Frequency characteristics of very fast transient currents in a 245-kV GIS," *IEEE Trans. Power Del.*, vol. 20, no. 4, pp. 2450–2457, Oct. 2005.

[14] C. M. Wiggins *et al*, "Electromagnetic transients in substations," *Electr. Power Syst. Res. Inst.*, Tech. Rep. 102006, Palo Alto, CA, USA, 1993.

[15] J. He, Z. Yu, R. Zeng, B. Zhang, S. Chen, and J. Hu, "Power-frequency voltage withstand characteristics of insulations of substation secondary systems," *IEEE Trans. Power Del.*, vol. 25, no. 2, pp. 734–746, Apr. 2010.

[16] A. Marinescu, S. Coatu, and D. Rucinschi, "About the EMC of non-conventional electronic instrument transformer case study," in *Proc. ICATE*, Oct. 2012, pp. 1–5.

[17] B. Djokic and E. So, "Calibration system for electronic instrument transformers with digital output," *IEEE Trans. Instrum. Meas.*, vol. 54, no. 2, pp. 479–482, Apr. 2005.

[18] *Electromagnetic Compatibility (EMC)—Part 4-18: Testing and Measurement Techniques—Damped Oscillatory Wave Immunity Test*, IEC Standard 61000-4-18, 2006.

[19] R. Hu *et al.*, "Transient enclosure voltage (TEV) measurement system of UHV GIS and TEV statistical characterization," in *Proc. EMC EUROPE*, Rome, Italy, Sep. 2012, pp. 1–6.

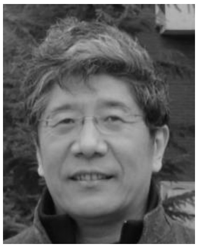
[20] H. Rong, X. Cui, W. J. Chen, W. D. Zhang, Z. B. Li, and M. Dai, "Experimental research on the characteristics of transient enclosure voltage in ultra high voltage gas insulated switchgear," (in Chinese), in *Proc. Chin. Soc. Electr. Eng.*, vol. 34, no. 29, pp. 5244–5258, Oct. 2014.

[21] H. T. Wu *et al*, "Characteristics of electromagnetic disturbance for intelligent component due to switching operations via a 1100 kV AC GIS test circuit," *IEEE Trans. Power Del.*, to be published.

[22] Q. Ma *et al.*, "Experimental study on secondary system grounding of UHV fixed series capacitors via EMI measurement on an experimental platform," *IEEE Trans. Power Del.*, vol. 27, no. 4, pp. 2374–2381, Oct. 2012.

HENG-TIAN WU was born in Shandong Province, China, in 1989. He received the B.Sc. degree in electrical engineering from North China Electric Power University, Beijing, China, in 2011, where he currently pursuing the Ph.D. degree. His main research interest is electromagnetic compatibility in power systems and electromagnetic interference problems in gas-insulated substations.

CHONG-QING JIAO was born in Hubei Province, China, in 1981. He received the B.Sc. degree in geophysics from the Chinese University of Geosciences, Wuhan, China, in 2002, and the Ph.D. degree in physical electronics from the Institute of Electronics, Chinese Academy of Sciences, Beijing, China, in 2007. He is currently an Associate Professor in electrical and electronic engineering with North China Electric Power University, Beijing, China. His current research interests are electromagnetic theory and applications, and the EMC in power system.



XIANG CUI (M'97–SM'98) was born in Baoding, Hebei Province, China, in 1960. He received the B.Sc. and M.Sc. degrees in electrical engineering from North China Electric Power University, Baoding, in 1982 and 1984, respectively, and the Ph.D. degree in accelerator physics from the China Institute of Atomic Energy, Beijing, China, in 1988.

He is currently a Professor and the Vice Director of the State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University. His research interests include computational electromagnetics, electromagnetic environment, and electromagnetic compatibility in power systems, insulation, and magnetic problems in high-voltage apparatus. He is a Standing Council Member of the China Electrotechnical Society and a fellow of IET. He is also an Associate Editor of the IEEE Transactions on Electromagnetic Compatibility.

XIAO-FAN LIU was born in Henan Province, China, in 1990. He received the M.Sc. degree in power systems from North China Electric Power University, Beijing, China in 2015. He is currently with the Economic Research Institute, State Grid Jiangsu Electric Power Company.

His main research interest is electromagnetic compatibility in power systems.

JIAN-FEI JI was born in Jiangsu Province, China, in 1982. He received the M.Sc. and Ph.D. degrees in signal and information processing from Harbin Engineering University, Harbin, China, in 2008 and 2012 respectively. He is currently with the Electric Power Research Institute, State Grid Jiangsu Electric Power Company.

His main research interests include signal processing and the EMC in power system.