Analysis on Back-Flow Surge in Wind Farms

Y. Yasuda and T. Funabashi

Abstract--When a wind turbine in a wind farm is struck by lightning, the phenomenon of surge invasion to the distribution line is categorized as "back-flow surge". It has been reported that this back-flow surge sometimes burns out surge arresters or breaks low-voltage circuits even far from the point of the lightning-struck. In practice, many such incidents that have occurred not only involved the wind turbine that was actually struck but also other affected wind turbines that had not been struck.

The present report analyzes incidents of burnout to surge arresters resulting from winter lightning at wind farms using PSCAD/EMTDC. Calculations were performed to clarify the mechanism of how the back-flow surge propagates to other turbines from the directly struck wind turbine.

The calculations clarified that burnout incidents could easily occur even in a turbine next to the lightning-struck one. It also became evident that burnout incidents can be reduced when interconnecting grounding wire are installed between wind turbines.

Keywords: wind power generation, wind turbine, lightning, surge arrester, grounding (earthing), transient analysis.

I. INTRODUCTION

As wind turbines have spread worldwide, lightning incidents have become regarded as a major issue. Compared with conventional electrical equipment, wind turbines, as the latest electrical apparatuses, have a unique shape and are very tall, open-air structures with an amount of low voltage circuits inside them. Because of their unique configuration, it has been suggested that such facilities are vulnerable to lightning damage [1]-[2]. It is necessary to employ protective measures that are different from those used with conventional electrical equipment. Although some reports, *e.g.* IEC TR61400-24, describe damage incidents and suggest conceptual methods for lightning protection for wind turbines, few investigations especially into grounding designs around wind turbine and wind farm have been reported.

Especially in Japan, which has a unique and relentless environment that includes the notorious "*winter lightning*" [3]-[6], active discussions about lightning protection for wind turbines are beginning to result [7]-[8]. While blade protection has been relatively well discussed, the effect of grounding design including "*interconnecting grounding*" remains to be clarified. The authors therefore considered that much work remained to be done in this area.

As well as serious damage to blades, the breakdown of low-voltage and control circuits have frequently occurred in wind farms worldwide. According to IEC TR61400-24, more than 50 % of failures in wind turbine equipment are those occurring in low-voltage, control, and communication circuits. Indeed, many dielectric breakdowns of low-voltage circuits and burnouts of surge arresters in wind turbines are reported. Such frequent problems in the low-voltage circuits may cause a deterioration of the utilization rate and consequently cause increases in the cost of power generation.

The phenomenon of surge invasion to the distribution line from a wind farm turbine that is struck by lightning is quite similar to the "*back-flow surge*" reported in [9]. In that report, the surge flowed from a customer's structure such as a communication tower into the distribution line. High resistivity soil often creates surge arresters for tower grounding systems to operate in reverse and allow reflux of the surge current to the grid. It is reported that this back-flow surge can sometimes burn out surge arresters or break down low-voltage circuits even on an electric pole far from the point of the lightning-struck.

Several breakdown and burnout incidents in low-voltage circuits and surge arresters at wind farms are thought to be the result of the above back-flow surge. In practice, many of the incidents that have occurred not only involved the actual lightning struck wind turbine but also other wind turbines that had not been struck. The reason why turbines that had not been struck were nevertheless damaged has not been fully explained.

The authors, therefore, investigated a wind farm using surge analysis [10]-[11]. The present report describes an analysis of incidents of burnout to surge arresters resulting from winter lightning at wind farms. Calculations using PSCAD/EMTDC transient simulators are performed to clarify the mechanism of how the back-flow surge propagates to other turbines from the wind turbine that has been directly struck by the lightning. The aim of the present analysis is to clarify the influence of grounding wire(s) of the distribution line in a wind farm. Reference [9] also noted that grounding wire(s) can reduce burnouts of surge arresters in the case of a communication tower. This paper tries to clarify if there is a similar effect from the installation of grounding wire(s) for wind farm lightning protection.

Y. Yasuda is with Department of Electrical Engineering and Computer Science, Kansai University, Osaka, Japan (corresponding author to provide phone: +81-6-6368-0978; fax: +81-6-6388-8843; e-mail: yasuda@kansai-u.ac.jp).

T. Funabashi is with Meidensha Corporation, Tokyo, Japan (e-mail: t.funabashi@ieee.org).

Presented at the International Conference on Power Systems Transients (IPST'07) in Lyon, France on June 4-7, 2007

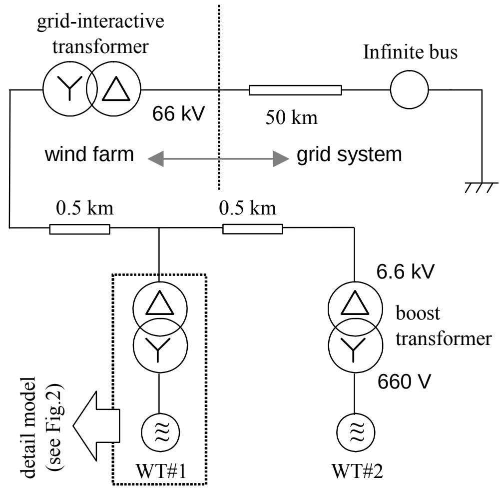

Fig.1 Wind farm model with 2 wind turbines

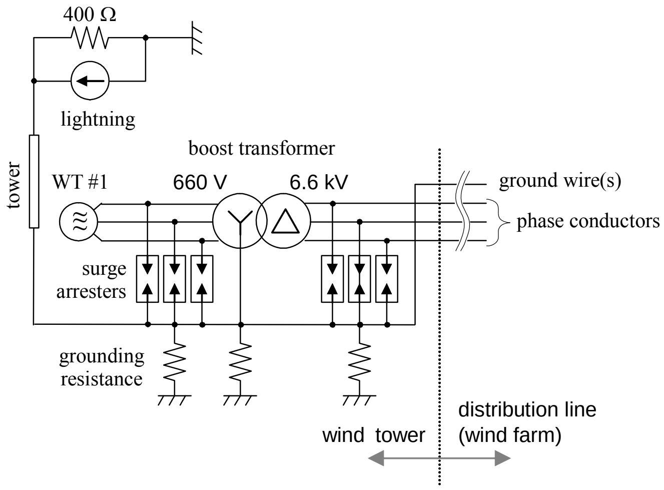

Fig.2 Detail model of each wind turbine

II. Model for Analysis

A. Wind Farm and Wind Turbine Models

Figure 1 shows a two turbine wind farm model, identical in performance and condition. Since we sought to simulate the burnout of surge arresters installed in a wind farm, we assumed that blade burnout or explosive destruction and dielectric breakdown at the turbine that had actually been struck was prevented by certain measures.

In this model, it is assumed that: (i) An array of 2 wind turbines of the 1 MW class at 0.4 km intervals is interconnected to the power grid system via a very high voltage grid-interactive transformer (6.6 kV / 66 kV). (ii) The surge impedance of the wind tower is determined as 164 Ω, which is estimated from an iron vertical conductor of 60-m height and 3.0-m radius, according to an experimental equation described in [12]. (iii) Although a wind power generator consists of a gear box, a synchronous or an induction generator, rectifier, 3-phase inverter, and so on, for this simulation a stable synchronous generator is presumed for simplicity. To simplify the calculation and evaluation, the synchronous generators have no output voltage. This will enable us to simply check one of the phase conductors, because the behavior under a lightning surge invasion from common grounding would essentially retain an equivalent of three phase. (iv) Boost transformers for the generators (660 V / 6.6 kV) are installed inside the wind turbine towers. Surge arresters are attached to the primary and secondary terminals and connected to a common grounding, as shown in the diagram in Fig.2. (v) The grounding resistance of each grounding point is simulated as 10 Ω. Thus, the total value of the interconnected grounding system of the wind turbines becomes 3.33 Ω. Other details and constants used in the model are shown in Table 1.

In the present transient analysis, we employed an EMPT-equivalent simulator; PSCAD/EMTDC ver.4.1.1, a digital simultaneous grid system analyser developed by the Manitoba HVDC Research Center [13]. An example of a PSCAD description of the present wind farm model with two turbines is illustrated in Fig. 3.

TABLE 1 ANALYSIS CONDITIONS.

Wind turbine (Synchronous Generator) model		
rating power [MVA]		1.0
rating voltage [kV]		0.66
impedance (R-L-C model)	resistance [Ω]	0.002
	inductance [mH]	0.231
	capacitance [μF]	0.001

Transformer model	(boost	grid)
connection method	Y / Δ	
rating power [MVA]	1.0	10.0
rating voltage [kV]	0.66 / 6.6	6.6 / 66
frequency [Hz]	60	
no load losses [p.u.]	0.0	
copper losses [p.u.]	0.005	
positive sequence leakage inductance [p.u.]	0.15	
saturation	no	
aircore reactance [p.u.]	0.2	
magnetizing current [%]	1.0	

Distribution Line Model in Wind Farm		
phase conductors	height of all conductors [m]	10
	configuration of conductors	horizontal
	spacing between phases [m]	0.7
	conductor radius [mm^2]	20.3
	sag for all conductors [m]	0.5
	number of sub-conductors in a bundle	1
ground wire	ground wire radius [mm^2]	5.5
	number of ground wire(s)	0, 1, 2
	height of ground wire(s) [m]	11
	spacing between ground wires [m] (in case of two wires)	0.7
	sag for all ground wires [m]	0.5
ground resistivity [Ωm]		100

B. Model of a Distribution Line in a Wind Farm

The distribution line in the present wind farm model is assumed as an overhead line with three phase conductors

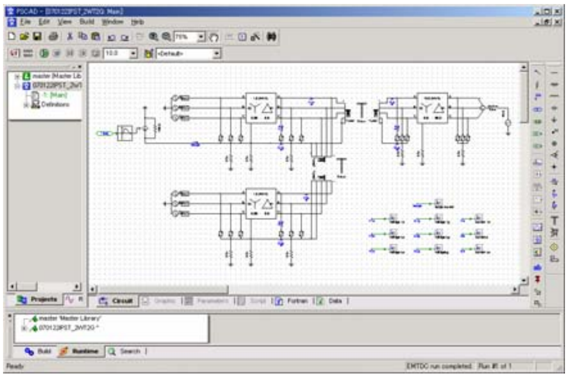

Fig. 3 PSCAD description of a wind farm model.

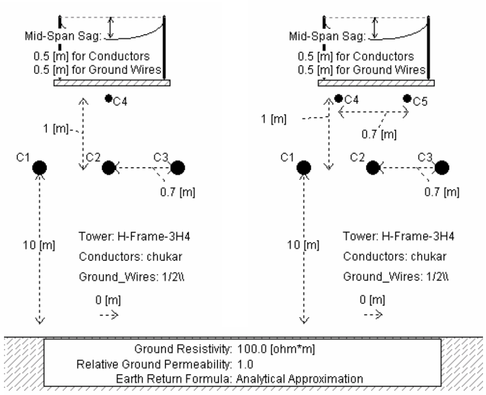

Fig. 4 Distribution line model in wind farm (by PSCAD description)
(Left: 1-ground-wire model, Right: 2-ground-wires model)

installed 10 m over the ground. Configuration details and parameters are shown in Fig.4 and Table 1.

The main aim of the present analysis is to confirm the effect of ground wire(s). Various conditions, therefore, are simulated: (1) "Case GW0": no ground wires are installed above the overhead line. (2) "Case GW1": one ground wire is tensioned 1 m above the three phase conductors. Both terminals of the ground wire are connected to the common grounding system of the wind turbines and the grid-interactive transformer. (3) "Case GW2": two ground wires horizontally separated at 0.7 m length above the conductors are installed. In PSCAD/EMTDC, the calculation model of an overhead distribution line obeys the Bergeron Method, which is similar to the widely used EMTP/ATP calculation.

C. Model of Winter Lightning

A standard summer lightning event is generally assumed to have a crest peak of 30 kA, a crest width of 2 μs, and a wave tail of 70 μs. By contrast, since winter lightning has varying crest widths and crest peaks; a standardized model has yet to be established. Therefore, in this report, the modeling of winter lightning is based on the model described in [11]. The parameters for crest peak, duration of wave tail and peak value are determined as 2 μs, 631 μs and 51 kA, respectively. These values are according to the 16 % statistic value from a cumulative frequency distribution of lightning current wave shape as detailed in [9].

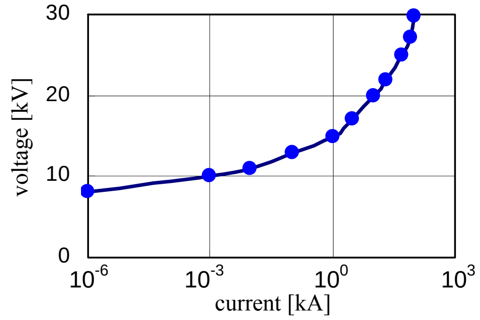

Fig.5. Linear-wise characteristics model for 2.5-kA surge arrester.

D. Model of a Surge Arrester and its Burn-out Model

To provide protection from surge invasion, it was assumed that surge arresters were installed in both the primary (low-voltage side; wind turbine side) and secondary (high-voltage side; grid side) terminals of the boost transformer near to each wind turbine. The nominal discharge current of the surge arrester was assumed to be 2.5 kA and its characteristic curve, starting at V_{1mA} = 8 kV, is shown in Fig.5.

The burn-out of an arrester depends on whether the heat produced by the current flowing through the arrester exceeds the thermal limit of the arrester. To calculate the total heat absorbed by the arrester E_{ar} [kJ] in the present analysis, it is necessary to specify the simultaneous power $p_{ar}(t)$ [W] derived from the arrester's terminal voltage $v_{ar}(t)$ [V] and the current flowing through the arrester $i_{ar}(t)$ [A]. Then, the total electric energy W_{ar} [Wh] can be calculated by integrating $p_{ar}(t)$ from 0 to the time T [s] when $i_{ar}(t)$ converges to 0 kA. The total thermal energy absorbed in the arrester E_{ar} [kJ] is given by unit conversion from W_{ar} [Wh]. This sequence is described by the following equations:

$$p_{ar}(t) = v_{ar}(t) \times i_{ar}(t) \qquad (2.1)$$

$$W_{ar} = \int_0^T p_{ar}(t)\,dt / 3600 \qquad (2.2)$$

$$E_{ar}\ [\mathrm{kJ}] = 3.6 \times W_{ar}\,[\mathrm{Wh}]\ . \qquad (2.3)$$

III. RESULTS OF TRANSIENT ANALYSIS

In this chapter, comparisons are made between the energy consumption of the surge arresters among the three cases with various numbers of ground wires. It is assumed that the lightning strikes wind turbine No.1 (WT#1), which is the nearest turbine to the grid.

A. Observation of Waveforms around Surge Arresters

Figure 6 sets out the results of EMTDC calculations in the cases of winter lightning strikes. Column (A) denotes the various waveforms measured around the surge arrester (phase a) installed at the high voltage terminal of the boost transformer of WT#1. In the WT#1 arrester, since the lightning surge invades to the common grounding system and operates the arrester in reverse, from ground to the line, the polarity of each waveform was inverted. Also, Columns (B) and (C) correspond to the waveforms around the arrester at WT#2 and the grid-interactive transformer, respectively. The phenomena of "back-flow surge" in the wind farm can easily be recognized.

On the other hand, the graphs in Row (1) show voltage waveforms between the terminals of the respective surge arresters. Row (2) is for current waveforms flowing through the arrester, and Row (3) is for simultaneous power according to Eq.(1), *i.q.* Every graph in Fig.6 has three curves due to the various conditions, *i.e.* Case WG0, Case WG1 and Case WG2.

Comparing Case WG0 and Case WG1, it can be clearly seen that the effect of the ground wire to reduce the surge reaching the next turbine and the grid transformer is quite significant. From the three graphs in Row (1), it is clear that the surge duration at every point in the wind farm is reduced by half. The surge current passing through the arrester shown in Row (2) is also cut down by almost half or two-thirds. Consequently, the simultaneous power produced in the surge arrester becomes much lower, as shown in Row (3).

B. Evaluation of the Possibility of the Surge Arrester Burning out

In Row (3) of Fig.6, the integral area surrounding the simultaneous power curve becomes equal to the thermal energy produced in the surge arrester. Summarizing the above integration, the bar graphs shown in Fig.7 are drawn to evaluate the possibility of a burnout accident at the surge arresters. Column (1) in Fig.7 illustrates the results of the integration area of simultaneous power curves, *i.e.* the energy consumption in each surge arrester. The graph of WT#1, which is directly struck by lightning, displays a tendency to produce huge thermal energy in the surge arresters. This suggests that there is a definite possibility of burnout incidents under the conditions found with huge winter lightning strikes. Since the total grounding resistance of the wind tower is assumed as 3.33 Ω in the present case, it becomes clear that a lower resistance or a higher rate for the surge arrester is needed to avoid burnouts.

The most important result presented in the present report is shown in Row (B) in Fig.7. From this graph of the energy consumption in the arrester of WT#2, the successful effect of installing ground wire(s) is evident. If a ground wire was not installed (Case GW0), a huge quantity of energy could surge in, even to the adjoining turbine that was not directly struck by the lightning. By contrast, in the case of ground wire employment (Case GW1), the surge energy invading to WT#2 is cut down to less than half. Moreover, the results for

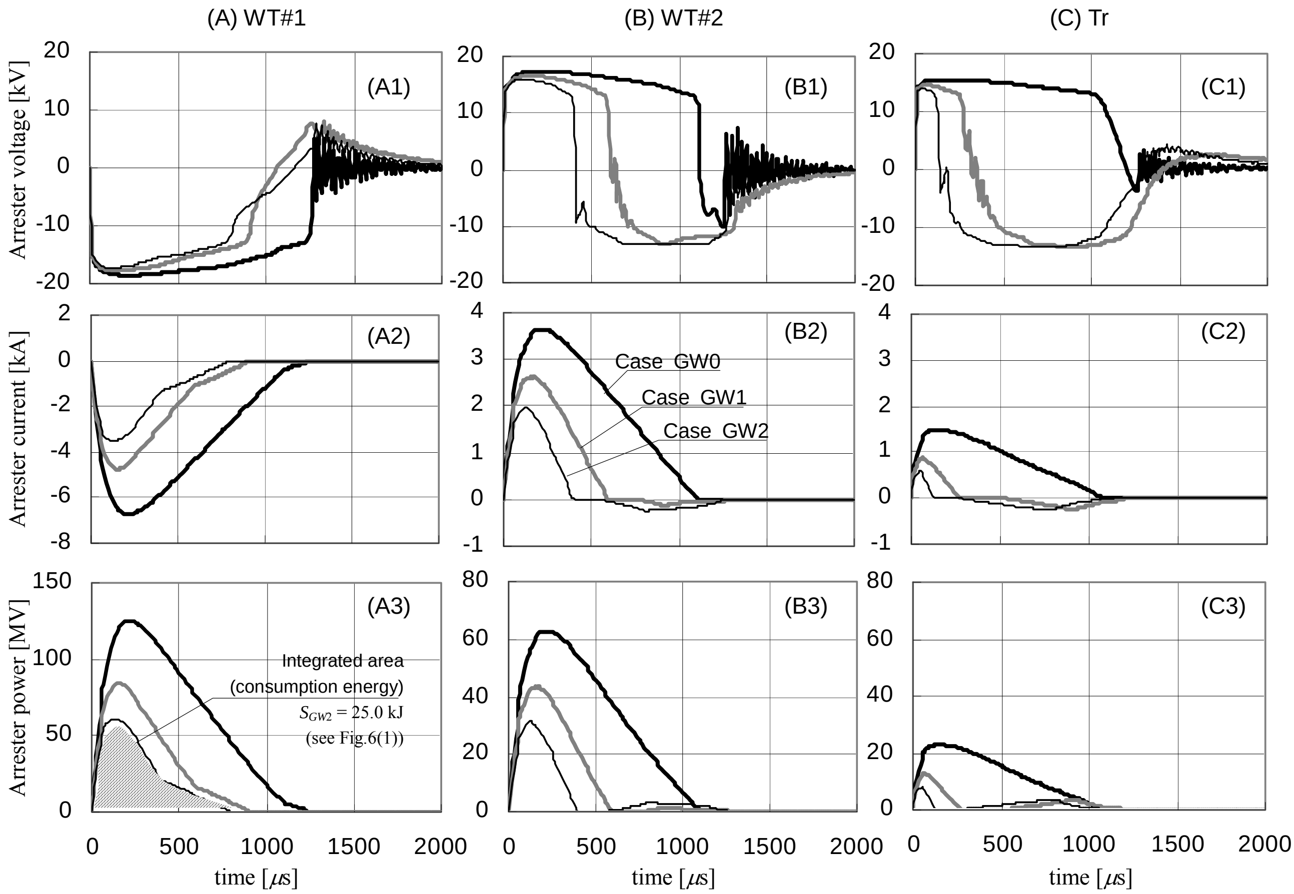

Fig. 6 Calculated waveforms at surge arresters at various points among the wind farm in case of summer lightning (2/631 μs, 51 kA).
(Column (A): wind turbine No.1 (WT#1), Column (B): wind turbine No.2 (WT#2), Column (C): grid-interactive transformer (Tr),
Row (1): voltage between terminals of arrester, Row (2): current through arrester, Row (3): simultaneous power consumed at arrester)

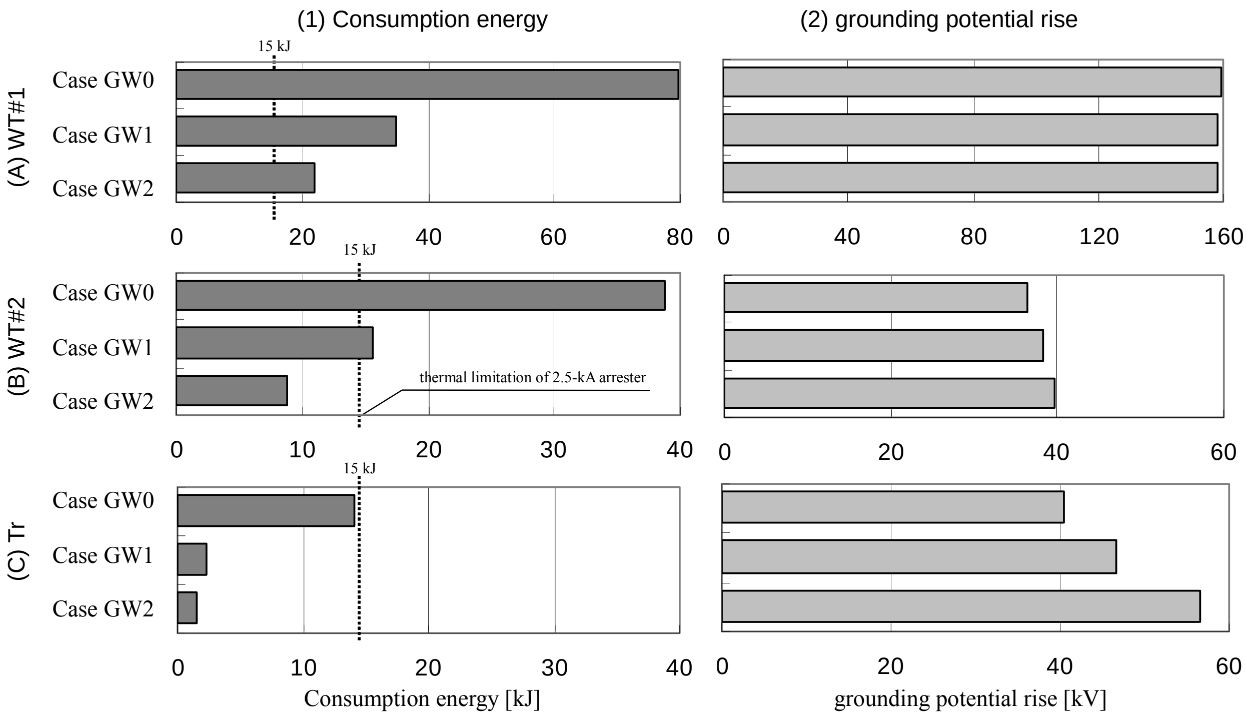

Fig.7. Energy consumption at surge arresters and maximum grounding potential rise at points around the wind farm in case of summer lightning (2/631 μs, 51 kA). (Column 1: total consumption energy at arrester, Column 2: maximum grounding potential rise, Row A: wind turbine No.1 (WT#1), Row B: wind turbine No.2 (WT#2), Row C: grid-interactive transformer (Tr).)

Case GW2 shows that the surge energy can be suppressed by much less than 15 kJ, which is the thermal limitation of a 2.5-kA class surge arrester.

A comparison between the different numbers of ground wires also gives an interesting result. From the results in Fig.7, a multiple ground wire strategy provides a further margin of safety against lightning surge. As a similar tendency, to that in the present calculation for the back-flow surge, is noted in the case of a communication tower in [9], it becomes evident that a back-flow surge in a wind farm can be reduced by the installation of ground wire(s).

C. Evaluation of Potential Rise of Grounding System

Finally, we need to also mention that a negative influence from a ground wire(s) installation. Column (2) of Fig.7 shows a surprising result. The graph of a grounding potential rise in WT#2 demonstrates an upward trend according to increases in the number of ground wires. The same tendency can be recognize in the result in the grid-interactive transformer (Tr). Even worse is that the additional installation of ground wires does not contribute very much to a reduction of the potential rise in WT#1's grounding system.

Another result of calculation in case of summer lightning (2/70 μs, 30 kA) is shown in Fig.8, where there is barely possibility of a surge arrester's burnout because the total energy of back-flow surge due to summer lightning is much smaller than that of winter lightning. From Fig.8, it is also evident that the potential rise at the equipments that are not struck by lightning tends to increase because of the installation of grounding wire(s). Comparing with the case of winter lightning, the altitude of the potential rise due to summer lightning is relatively small. However, there still remains negative impact given by the grounding wire(s).

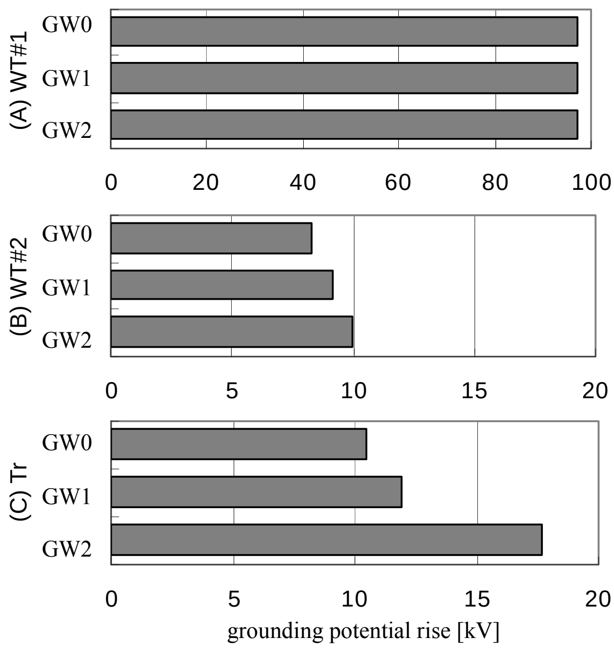

Fig.8. Maximum grounding potential rise at points around the wind farm in case of summer lightning (2/70 μs, 30 kA)

The reason of this negative impact seems to be because a grounding wire of 0.4 km has relatively strong inductive impedance against a high frequency domain of more than 1MHz, such as found in a lightning surge. However, since the current flowing through the interconnecting ground wire tends to be large, the grounding potential rise of the next turbine or a grid-transformer displays an increasing tendency. This may give rise to a possibility of breakdowns of low voltage circuits inside the wind turbine. As indeed already suggested in several reports [14]-[15]; the present result agrees with these reports and confirms the problem. While it can be concluded that a grounding wire strategy is very effective against winter lightning, it may cause unexpected effects in the case of summer lightning.

IV. Conclusions

The present report presented an analysis concerning incidents of burnouts of surge arresters resulting from winter lightning at wind farms using PSCAD/EMTDC. Calculations were performed to clarify the mechanism of how back-flow surge propagates from the wind turbine directly struck by the lightning to other turbines.

The calculations, with various conditions, *e.g.* the number of interconnecting ground wires, demonstrated that burnout incidents can be reduced by installing multiple ground wires to the distribution line in a wind farm. However from the viewpoint of the potential rise, the ground wire does not help to reduce the potential rise of wind turbines and the grid-interactive transformer.

Consequently, the result of the present calculation suggests that an accurate grounding design and an LPS strategy must be implemented for wind turbines situated in wind farms. If a wind farm is to be constructed in an area affected by heavy winter lightning, multiple ground wires and higher rated surge arresters should be installed to avoid burnouts of the surge arresters and other equipment. If the wind farm also potentially suffers from summer lightning, the installation of ground wire(s) is not recommended because the interconnection of ground wires does not have a good effect on reducing the potential rise. In both cases, trials to reduce grounding resistance should be selectively done for the particular turbine that would tend to suffer from lightning because of the prevailing wind direction or geographical condition.

Though the present analysis is only a fundamental calculation in principle, the authors hope the results will help further the development of LPS technology for wind power generation.

References

[1] "Wind Turbine Generation System – 24: Lightning Protection", IEC Technical Report, TR61400-24, 2002.

[2] B. McNiff: "Wind Turbine Lightning Protection Project 1999-2001", NREL Subcontractor Report, SR-500-31115, 2002.

[3] S. Yokoyama, K. Miyake, T. Suzuki, S. Kanao: "Winter Lightning on Japan Sea Coast – Development of Measuring System on Progressing Feature of Lightning Discharge –", *IEEE Transaction on Power Delivery*, **5**, pp.1418-1425, July 1990.

[4] K. Miyake, T. Suzuki, M. Takashima, M. Takuma, T. Tada; "Winter lightning on Japan Sea coast-lightning striking frequency to tall structures", *IEEE Transactions on Power Delivery*, **5**, 3, pp.1370-1376, July 1990.

[5] K. Miyake, T. Suzuki, K. Shinjou: "Characteristics of winter lightning current on Japan Sea Coast", *IEEE Transactions on Power Delivery*, **7**, 3, pp.1450-1457, July 1992.

[6] H Motoyama, K. Shinjo, Y. Matsumoto, N. Itamoto: "Observation and analysis of multiphase back flashover on the Okushishiku Test Transmission Line caused by winter lightning", *IEEE Transactions on Power Delivery*, **13**, 4, pp.1391-1398, Oct. 1998.

[7] A. Wada, S. Yokoyama, T. Numata, T. Hirose: "Lightning Observation on the Nikaho-Kogen Wind Farm", Proc. of *International Workshop on High Voltage Engineering* (*IWHV '04*), volume 1, pp.51-55 (The papers of *Joint Technical Meeting on Electrical Discharges, Switching and Protecting Engineering and High Voltage Engineering*, IEE Japan, **ED-04**-118, **SP-04**-29, **HV-04**-59) (2004).

[8] "Chapter 13: Japan", in "IEA Wind 2004 Annual Report", pp.147-154 (2005).

[9] K. Nakada,T. Wakai, H. Taniguchi, T. Kawabata, S. Yokoyama, T. Yokota, A. Asakawa: "Distribution arrester failures caused by lightning current flowing from customer's structure into distribution lines", *IEEE Transactions on Power Delivery*, **14**, 4, pp.1527-1532, Oct. 1999.

[10] Y. Yasuda, T. Funabashi: "Transient Analysis on Wind Farm Suffered from Lightning", Proc. of *39th International Universities Power Engineering Conference*, pp.202-206. Sept. 2004.

[11] Y. Yasuda, T. Funabashi: "Lightning Analysis on Wind Farm – Sensitivity Analysis on Earthing –", Proc. of *27th International Conference on Lightning Protection*, pp.1041-1046, Sept. 2004.

[12] T. Hara and O. Yamamoto: "Modelling of a transmission tower for lightning-surge analysis", Proc. IEE, **143**, 3, pp.283-289 (1996).

[13] Manitoba HVDC Research Center: "Welcome to PSCAD", `http://pscad.com/`

[14] I. Cotton: "Windfarm Earthing", Proc. of *11th International Symposium on High Voltage Engineering* (*ISH99*), volume 2, pp.288-291 (1999, 8).

[15] B. Hermoso: "Wind Farm Earthing Installations: Rated and Lightning Frequencies Behaviour", Proc. of *International Conference on Grounding and Earthing* (*GROUND'2006*), pp.411-414 (2006, 11).

Yoh Yasuda was born in Tokyo, Japan, in 1967. He graduated from the Department of Electronics and Information Engineering, Yokohama National University, Japan in 1989 and received a Ph.D. (Engineering) from Yokohama National University in 1994. Since 1994 he has been with the Department of Electrical Engineering (presently the Department of Electrical Engineering and Computer Science), Kansai University, Japan, where he is presently an associate professor. His current research interests are the development of dispersed generation systems with small vertical-axis wind turbines (VAWT) and lightning protection of wind farms with large horizontal-axis wind turbines (HAWT).

He is a member of IEEE, European Wind Energy Association, World Wind Energy Association, Japan Wind Energy Association, Japan Solar Energy Society, Japan Institute of Energy, Institute of Electrical Installation Engineers of Japan, and IEE of Japan.

Toshihisa Funabashi was born in Aichi, Japan, in 1951. He graduated in March 1975 from the Department of Electrical Engineering, Nagoya University, Aichi, Japan. He received, in March 2000, a Doctoral degree from Doshisha University, Kyoto, Japan. He joined Meidensha Corporation in April 1975 and has engaged in research on power system analysis. Currently, he is the Senior Engineer of the Power Systems Engineering Division. Dr. Funabashi is a chartered engineer in the UK, a senior member of IEEE, and a member of the IET and the IEE of Japan.