Impact Analysis of Wind Farms in the Jeju Island Power System

Eel-Hwan Kim, Jae-Hong Kim, Se-Ho Kim, Jaeho Choi, *Member, IEEE,* Kwang Y. Lee, *Fellow, IEEE,* and Ho-Chan Kim

***Abstract*—This paper presents modeling and impact analysis of wind farms in Jeju island power system, which is made of wind farms, a current source-type high-voltage, direct current (HVDC) system, and thermal power plants. In this paper, four kinds of major components are modeled: a total of 88 MW wind farms, a 300 MW HVDC system, thermal power plants, and the Jeju power system load. To analyze the impact of the wind power generation to the Jeju power system, simulation is carried out for two case studies by using the PSCAD/EMTDC program. One is for the steady-state operation under different wind speed, and the other is for the transient-state operation when all wind farms are disconnected suddenly from the Jeju power grid due to the wind speed higher than the rated value. These comparative studies have been effective in accessing the impact of wind power generation on the Jeju island power system stability.**

***Index Terms*—Power quality, PSCAD/EMTDC, wind power generation.**

I. Introduction

In RECENT years, the wind power generation has become a very attractive utilization of renewable energy because it is now possible to improve the capability of capturing wind energy with the development of advanced power electronics technology. It has been a trend in wind power generation to combine a number of large-scale wind turbine generation systems (WTGS) and build a grid-connected wind farm [1], [2]. The location for a wind farm is usually determined by the wind speed, and therefore the wind farm is concentrated in specific areas. The wind in Jeju island is the strongest in Korea and the island has the best condition for wind power generation [3], [4]. The annual wind speed in the east and west coasts of the island is about 7–8 m/s, which is the reason why many companies are investing to construct wind farms in these areas [5]–[7].

However, there are some constraints on penetration of wind power generation to the Jeju power system due to the wind velocity distribution and weak power load. First of all, total power generation capacity in Jeju island including import through the high-voltage, direct current (HVDC) system from the mainland Korea is only about 730 MW, and the installed capacity of the wind power generation should be limited to guarantee the power system stability. In 2010, a total capacity of 88 MW wind power generation systems was under operation and about a total of 412 MW systems including off-shore wind farms will be supplemented by 2020 in Jeju island. Therefore, how much capacity of wind farm is acceptable without any harmful effects on the stability of the Jeju power system is one of the important issues. It was recommended strongly that the impact of wind power generation to the Jeju power grid be analyzed before penetrating more wind farms to the grid [8].

In this paper, two kinds of simulations are carried out for the analysis of the impact of wind farms by using the PSCAD/EMTDC program, which is widely favored tool for analysis of power system involving power electronics devices [9], [10]. One is the steady-state operation under different wind speed, and the other is the transient-state operation when all wind farms in the island are disconnected suddenly from the Jeju power grid due to the wind speed higher than the rated value. It is very useful to analyze the variation of grid voltage and frequency under the transient state to understand the impact of wind power generation in Jeju island power system.

This paper is organized as follows. The characteristics of Jeju power system and wind data are presented in Section II, modeling and simulation of Jeju system and wind turbine are given in Section III along with the discussion of the results, and conclusions are drawn in Section IV.

II. Characteristics of Power System and Wind Velocity in JeJu Isalnd

A. Power System in Jeju Island

Although small, the power system in Jeju island has many kinds of power system components, including thermal power plants, transmission and distribution networks, HVDC, and renewable energy systems. It shows that the probability of

Manuscript received September 22, 2010; revised January 8, 2011; accepted May 25, 2011. Date of publication August 30, 2011; date of current version February 23, 2012. This work was supported in part by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning grant funded by the Korea Government, Ministry of Knowledge Economy, under 2007-P-EP-HM-E-09-0000, and in part by a research grant from the Chungbong Academy Research Fund of Jeju National University in 2008.

E.-H. Kim, J.-H. Kim, S.-H. Kim, and H.-C. Kim (corresponding author) are with the Department of Electrical Engineering, Jeju National University, Jeju 690-756, Korea (e-mail: ehkim@jejunu.ac.kr; larry55@hanmail.net; hosk@jejunu.ac.kr; hckim@jejunu.ac.kr).

J. Choi is with the School of Electrical Engineering, Chungbuk National University, Cheongju 361-763, Korea (e-mail: choi@chungbuk.ac.kr).

K. Y. Lee is with the Department of Electrical and Computer Engineering, Baylor University, Waco, TX 76798 USA (e-mail: kwang_y_lee@baylor.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JSYST.2011.2163017

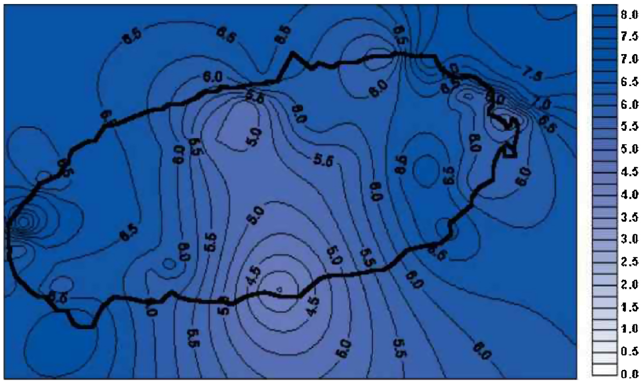


Fig. 1. Wind map of Jeju island.

electric fault is high and will be increased as the use of renewable energy sources is increased, debasing power system stability in the island. On the contrary, the rate of annual load increase is about 8–9%, which is faster than that of the mainland Korea. As the island is to become an international free-trade zone, the need for reliable supply of electricity is increasing. Not only the supply of energy but also the quality of power is becoming an important issue to meet the expectation of international standard in building the infrastructures. Therefore, the expansion of generation facilities is an essential requirement for securing power system stability and reliability in Jeju island. Furthermore, since the island is located in a hurricane path and it is known to have frequent lightening, there has been frequent contingencies on the system, which is heavily dependent on the HVDC tie from the mainland Korea and sporadic intermittent generation from small wind farms located in the east and west coasts of the island. The total installed capacity of Jeju island in 2010 is 730 MW, which includes 150 MW import through the HVDC system from the mainland. The power transfer through the HVDC is about 40% of the minimum load demand, which is almost 335 MW in 2010.

B. Wind Characteristics of Jeju Island

Fig. 1 shows the wind distribution map of Jeju island. Considering the map, the mean wind speed in the east and west coasts is almost 6–8 m/s, while in the north and south it is 4–6 m/s, implying that the east and west coasts have better condition for wind power generation than the north or south coasts. Recently, there have been many wind farms under construction in the east and west coasts and about 88 MW systems are installed cumulatively.

III. Modeling and Simulation

To verify the feasibility of increased penetration of wind energy, computer simulations have been carried out with a 1.5 MW NEGMICON WTGS, named NM72C, and Vestas V90 3 MW DFIG system, the current source type HVDC system, and thermal power plants including diesel engines and steam turbine generators; and, Jeju power grid load are also modeled in the simulation [11], [12].

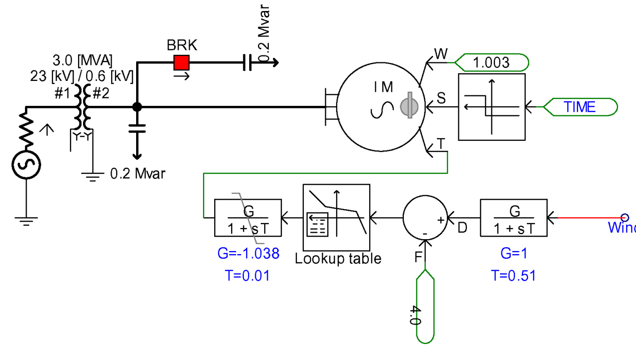


Fig. 2. WTGS model.

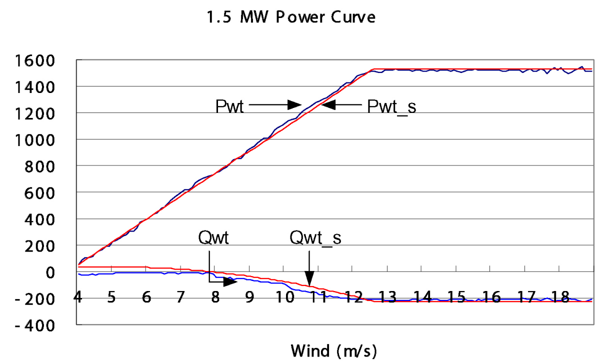


Fig. 3. Power performance curve of the WTGS system.

A. Wind Turbine Modeling

Fig. 2 shows the modeling scheme of the WTGS in the PSCAD program.

In the process of modeling the WTGS, it is very difficult to know all of the model parameters because the WTGS is a very complex system composed of many mechanical, electrical, and aerodynamic systems. Therefore, experiments were performed to model the system using the input and output data, where input being the wind speed and the output being the power output, resulting in the power performance curve. Using the real output data of a WTGS unit located in HanGeong wind farm installed in 2006 in the western Jeju island, the power performance curve was obtained and was made into a look-up table. In the look-up table, the increment in wind speed is 0.1 m/s, and output data is the mean value, which is derived from more than 15 data points sampled at different wind speeds.

Fig. 3 shows the simulation results of the model system and the real mean power output measured from January 2007 to February 2007 in HanGeong wind farm. In the figure, $P_{\rm wt}$ and $Q_{\rm wt}$ represent the real active and reactive power of the WTGS, respectively, and $P_{\rm wts}$ and $Q_{\rm wts}$ are the corresponding simulation results using the PSCAD/EMTDC program. Comparing the two results, the simulation model of WTGS is good to be used for power system analysis.

B. Power System Modeling of Jeju Island

Fig. 4 shows the PSCAD/EMTDC model of Jeju island power system. There are five types of components: thermal power plants, HVDC system, wind farms, transmission lines,

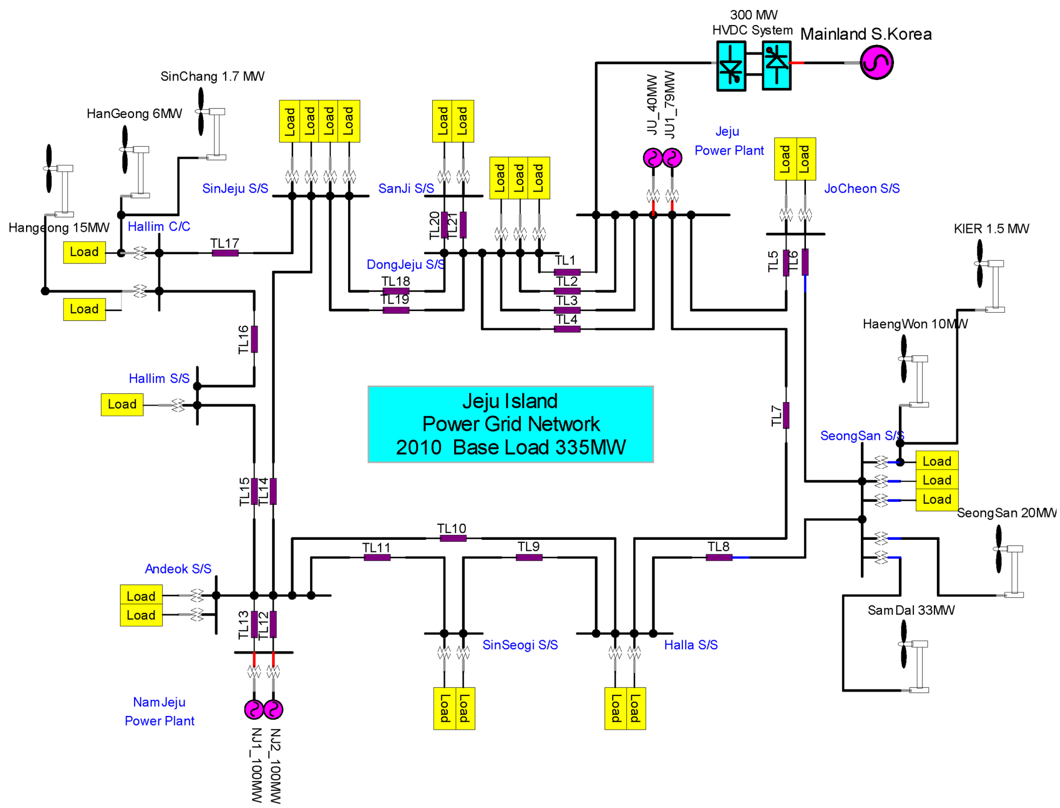


Fig. 4. PSCAD model of Jeju island power system.

TABLE I
PARAMETERS OF POWER PLANTS

		Ju_40 MW	Ju_79 MW	NJ1_100 MW NJ2_100 MW
Type		Diesel Turbine	Steam Turbine	Steam Turbine
Power rating (MW)		40	79	100
H (MW*s/MVA)		6.71	6.90	5.93
Open circuit time constant (s)	T'_{do}	7.60	2.75	10.30
	T''_{do}	0.087	0.047	0.046
	T'_{qo}	0.067	0.127	0.093

TABLE II
PARAMETERS OF HVDC SYSTEM

		HVDC	Synchronous Condenser
Type		Current Source	Gas Turbine
Power rating		300 MW	70 MVA
H (MW*s/MVA)		–	1.86
Open circuit time constant (s)	T'_{do}	–	11.3
	T''_{do}	–	0.05
	T'_{qo}	–	3.1

and the loads. On the assumption of 335 MW base load in Jeju island, the supply of electric power is from three kinds of power generation systems: thermal power plant composed of a 40 MW diesel engine, one 79 MW and two 100 MW steam turbine generation systems, the HVDC system supplying the power from 40 MW to 150 MW in frequency control mode, and wind farms located in seven different sites supplying power up to the maximum of 88 MW under variable wind speed. The system parameters for thermal plants and the HVDC system are listed in Tables I and II.

In the actual power system of Jeju island, it is possible to supply nearly 150 MW by the HVDC system during the constant power control mode. But, in the frequency control mode, the power supply capacity is from 40 MW to 150 MW depending on the load and power generation.

C. Simulation Results and Discussion

In Fig. 4, it is assumed that there are seven wind farms with 1.5 MW, 6 MW, 10 MW, 10.5 MW, 20 MW, 15 MW, and 33 MW power ratings, and all of these systems generate power according to the variable wind speed with the mean value of 10 m/s. It is assumed that the base load is rated at 335 MW, and the ratio of power supply is about 170 MW from thermal power plants versus 150 MW from the HVDC operating in frequency control mode. This implies that the HVDC system can absorb the output variation of the intermittent wind power generation due to variable wind speed. This simulation will be very useful for ensuring the stability of Jeju island power system while increasing the penetration of wind power generation.

To verify the effectiveness of proposed modeling system, four different variable wind velocities for different wind farms are used as shown in Fig. 5. Figs. 6 and 7, respectively, show

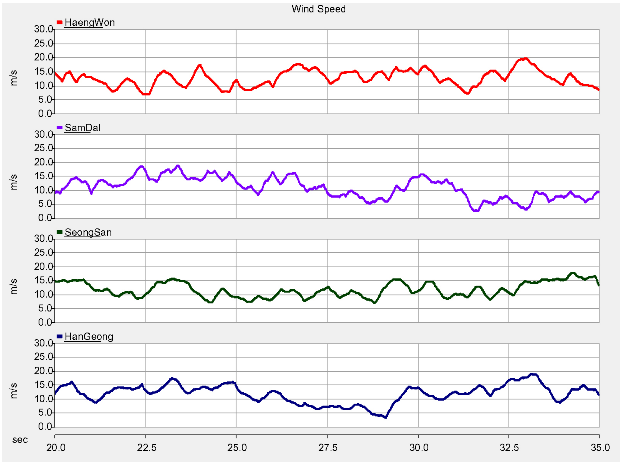


Fig. 5. Wind velocities in wind farms.

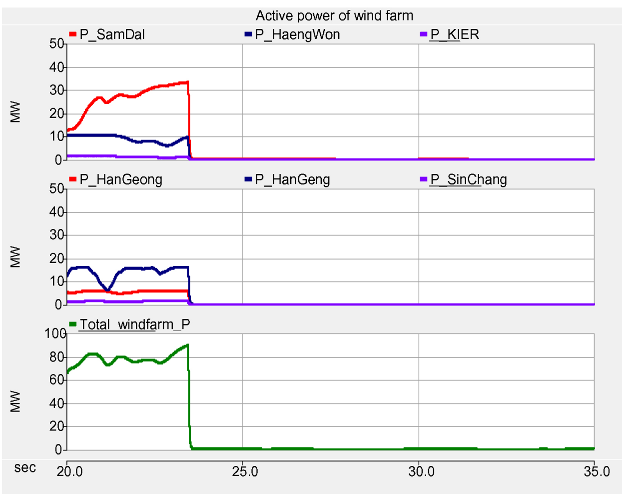


Fig. 6. Active power outputs of wind farms.

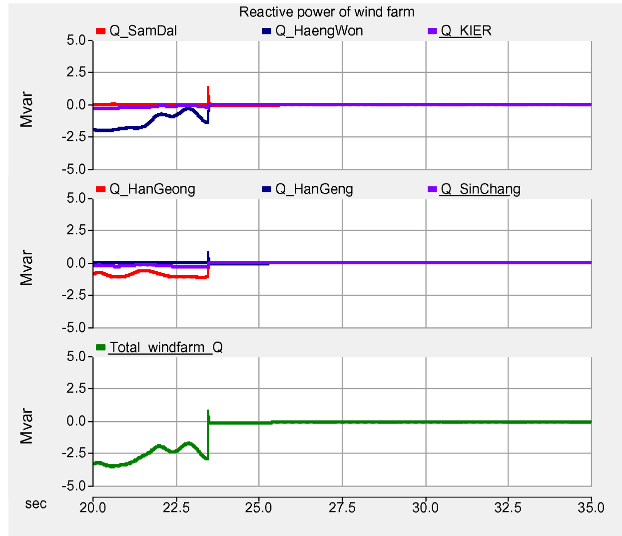


Fig. 7. Reactive power outputs of wind farms.

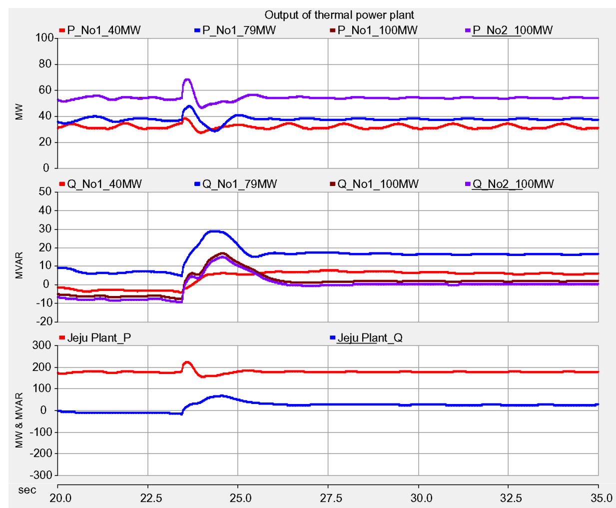


Fig. 8. Power outputs of thermal power plants.

the active and reactive power outputs of wind farms shown in Fig. 4. It is shown that the output of wind farms follow the variable wind speed very closely.

To analyze the transient characteristics of voltage and frequency in Jeju island power system, all wind farms were shut down at 23.4 s when the wind speed exceeded the rated speed. In Figs. 6 and 7, the total active output power of wind generation is changed from about 88 MW to 0 and the reactive power from −2 MVAR to 0.

When the wind farms were dropped, thermal power plant and the HVDC system responded immediately to cover the loss of wind power generation. Fig. 8 shows the active and reactive output powers of each thermal power plant. In the top figure, the active outputs of the two 100 MW steam turbine engines have the same performance due to parallel operation; thus, simulation results are overlapped and shown as one line. The bottom figure shows that the total thermal power, Jeju Plant_P, is equal to the total amount of the active power. In the figure, 40 MW diesel engine which has the 6.71 s response time generates the oscillating power ripple of ±5% of the rated value. Both of the 100 MW steam-turbine generators which have the 5.93 s response time have faster response than the 79 MW steam-turbine generator, which as 6.9 s response time.

The values of the peak to peak ripple in Fig. 8 are about 2, 11, and 15 MW for 40, 75, and 100 MW generators, respectively.

In summary, the active and reactive output variations of all of the thermal power plants, wind farms, and the HVDC system are shown in Fig. 9. When the wind farm is tripped, the system frequency drops instantaneously and thermal plants respond immediately due to the governor response, followed by the HVDC picking up the balance of the load. Since the HVDC is coupled to a synchronous condenser with slow dynamics to supply reactive power, the HVDC system responds at a slower rate. As the HVDC system picks up the balance of the load, the thermal plants reduce generation and return to the scheduled set points with slight negative swing.

The total power output of the thermal power plants in steady state experiences very little effect resulting from the loss of

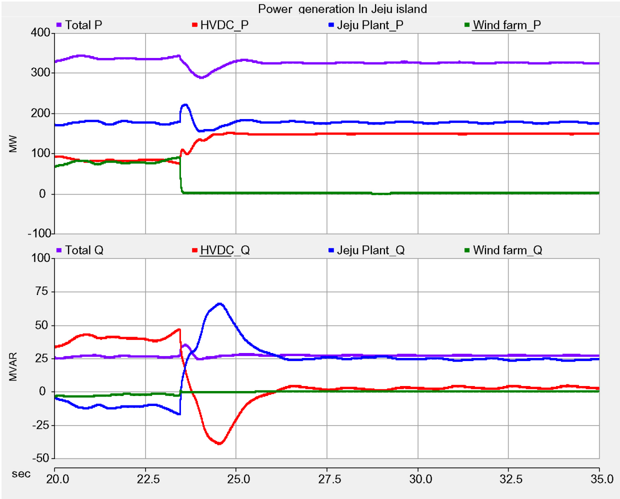


Fig. 9. Active power and reactive power variations in Jeju island.

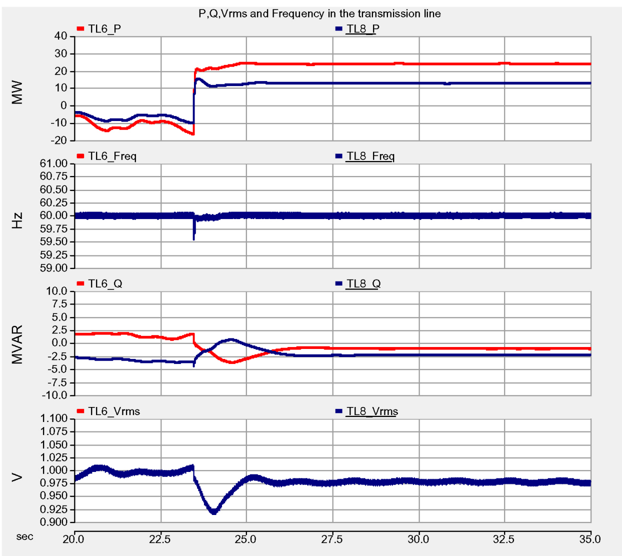


Fig. 10. Voltage and frequency in transmission lines.

wind power output, except during the transient period at 23.4 s. According to this simulation, the variation of wind power generation can be absorbed by the HVDC system, and thus the HVDC system will play an important role in ensuring the stability of Jeju island power system.

Fig. 10 shows the characteristics of voltage and frequency in transmission lines TL6 and TL8, which are linked to the SeongSan substation (S/S) in the east coast. In the simulation results, the frequency is almost constant except from 23.4 s to 26.3 s, at which time, the value of frequency drop is 0.5 Hz during the transient period.

In the transmission line, the variation of voltage magnitude has small ripple due to the variation of wind power generation and the oscillation of thermal power plant outputs. During the steady state, the variation of voltage magnitude is below 0.01 per-unit (pu). But, during the transient period, the voltage drop is about 0.08 pu for 2.9 s. This implies that the sudden change in wind power generation affects the power quality in the transmission system.

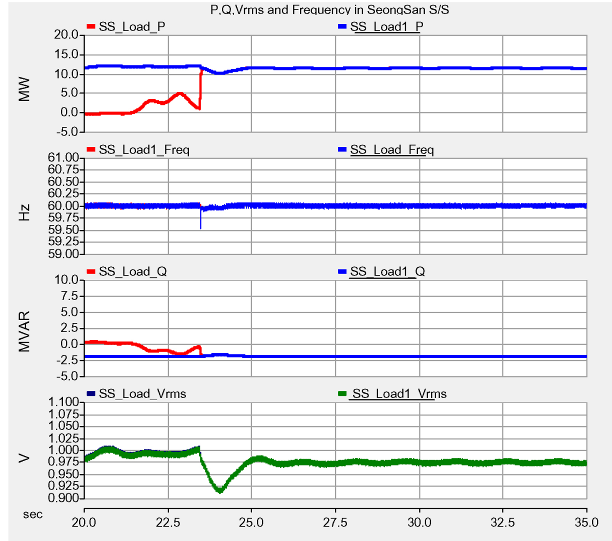


Fig. 11. Voltage and frequency at the load.

Fig. 11 shows the characteristics of voltage and frequency in the load connected to SeongSan S/S under the same condition as in Fig. 10. The characteristics of the simulation results are almost the same. But the value of frequency drop in the load is larger than that of the transmission line. According to this result, it is verified that the impact of wind farms on power quality is more severe in the distribution system than in the transmission system.

IV. Conclusion

Modeling and impact analysis of wind farms in the Jeju island power system, consisting of thermal power plants, HVDC system, and seven wind farms, have been performed under variable wind speed using the PSCAD/EMTDC program.

In the simulation study, it has been shown that the variable power generation of intermittent wind farms has effects on the active and reactive power generation of thermal plants in steady state. In transient state, when the wind farms were shut down due to high wind gust, the HVDC system was able to pick up the power lost from the wind farms, and yet not affecting the thermal plants in steady state. Since wind farms are connected in the distribution system, the loss of wind farms affected the power quality in the distribution system the most, in both frequency and voltage magnitude.

References

[1] T. Ackermann, *Wind Power in Power Systems*. New York: Wiley, 2005.

[2] M. G. Simoes and F. A. Farret, *Renewable Energy Systems: Design and Analysis with Induction Generator*. Boca Raton, FL: CRC Press, 2004.

[3] K. Y. Lee, S.-H. Kim, E.-H. Kim, and H.-C. Kim, "Fuel cell as an alternative distributed generation source under deregulated power system," *KIEE Trans. B*, vol. 55A, no. 12, pp. 561–568, 2006.

[4] K. Y. Lee and S.-H. Kim, "Progress in distributed generation in Korea," in *Proc. IEEE Power Eng. Soc. Gen. Meet.*, Jun. 2007, pp. 1–6.

[5] L. Wu, J. G. Park, J. S. Choi, and K. Y. Lee, "Effect of correlation coefficient of wind speed on the probabilistic reliability evaluation of power system considering wind turbine-generator," in *Proc. KIEE Spring Meet.*, May 2009.

[6] L. Wu, J. G. Park, J. S. Choi, K. Y. Lee, A. A. El-keib, and J. Watada, "A study on wind speed prediction using artificial neural network at Jeju island in Korea," in *Proc. 6th Int. Symp. Manag. Eng.*, no. 1616. Aug. 2009.

[7] L. Wu, J. G. Park, J. S. Choi, and K. Y. Lee, "A study on wind speed prediction using artificial neural network at Jeju island in Korea," in *Proc. IEEE T&D ASIA*, Oct. 2009, pp. 1–4.

[8] O. Anaya-Lara and F. M. Hughes, "Influence of wind farms on power system dynamic and transient stability," *Wind Eng.*, vol. 30, no. 2, pp. 107–123, 2006.

[9] *PSCAD/EMTDC User's Manual*, Manitoba HVDC Research Centre, Winnipeg, MB, Canada, 2006.

[10] *ABB Handbook: HVDC Light Topology*, ABB Ltd., Zürich, Switzerland, 1999.

[11] S. K. Anita and L. J. Teo, "Windmill modeling consideration and factors influencing the stability of a grid-connected wind power-based embedded generator," *IEEE Trans. Power Syst.*, vol. 18, no. 2, pp. 793–802, May 2003.

[12] A. D. Hansen, P. Sorensen, F. Lov, and F. Blaabjerg, "Initialization of grid-connected wind turbine models in power system simulations," *Wind Eng.*, vol. 27, no. 1, pp. 21–38, 2003.

Eel-Hwan Kim received the B.S., M.S., and Ph.D. degrees in electrical engineering from Chung-Ang University, Seoul, Korea, in 1985, 1987, and 1991, respectively.

He was a Visiting Scholar with the Ohio State University, Columbus, in 1995, and the University of Washington, Seattle, WA, in 2004. He is currently a Professor with the Department of Electrical Engineering, Jeju National University, Jeju, Korea. His current research activities include power electronics and control, which includes the drive system, renewable energy control applications, and power quality.

Jae-Hong Kim received the B.S. and M.S. degrees in electrical engineering from Jeju National University, Jeju, Korea, in 2000 and 2002, respectively, where he is currently pursuing the Ph.D. degree.

His current research interests include power electronics and control, which include the drive system, renewable energy control, and power saving applications.

Se-Ho Kim received the M.S. and Ph.D. degrees in electrical engineering from Yonsei University, Seoul, Korea, in 1985 and 1992, respectively.

Currently, he is a Professor with the Department of Electrical Engineering, Jeju National University, Jeju, Korea. He was a Visiting Scholar with the Pennsylvania State University, University Park, in 2007. His current research interests include power systems and renewable energy system operation.

Jaeho Choi (M'89) received the B.S., M.S., and Ph.D. degrees in electrical engineering from Seoul National University, Seoul, Korea in 1979, 1981, and 1989, respectively.

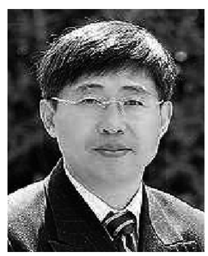
From 1981 to 1983, he was with the Jungkyoung Technical College, Daejeon, Korea, as a full-time Lecturer. Since 1983, he has been with the School of Electrical Engineering, Chungbuk National University, Cheongju, Korea, where he is currently a Professor. In 1993, 1998, 2003, and 2009, he was a Visiting Professor with the University of Toronto, Toronto, ON, Canada, and a Danfoss Visiting Professor with the Aalborg University, Aalborg, Denmark, in 2000. His current research interests include power electronics, power quality problems and solutions, energy storage systems, and renewable energy and micro-grid systems.

Dr. Choi is an active member of KIEE and KIPE. Currently, he is the Editor-in-Chief of the *Journal of Power Electronics*.

Kwang Y. Lee (F'01) received the B.S. degree from Seoul National University, Seoul, Korea, in 1964, and the M.S. degree from North Dakota State University, Fargo, in 1968, both in electrical engineering, and the Ph.D. degree in system science from Michigan State University, East Lansing, in 1971.

He is currently a Professor and Chair of electrical and computer engineering with Michigan State University, Oregon State University, Newport, University of Houston, Houston, TX, the Pennsylvania State University, University Park, and Baylor University, Waco, TX. His current research interests include power system control, operation, planning, and intelligent system applications to power systems.

Dr. Lee is an Editor of the IEEE TRANSACTIONS ON ENERGY CONVERSION. He was an Associate Editor of the IEEE TRANSACTIONS ON NEURAL NETWORKS. He is also a Registered Professional Engineer.



Ho-Chan Kim received the B.S., M.S., and Ph.D. degrees in control and instrumentation engineering from Seoul National University, Seoul, Korea, in 1987, 1989, and 1994, respectively.

From 1994 to 1995, he was a Research Staff Member with the Korea Institute of Science and Technology, Seoul. Since 1995, he has been with the Department of Electrical Engineering, Jeju National University, Jeju, Korea, where he is currently a Professor. In 1999 and 2008, he was a Visiting Scholar with the Pennsylvania State University, University Park. His current research interests include wind power control, electricity market analysis, and grounding systems.