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Evaluation of the Wind Power Penetration Limit and Wind Energy Penetration in the Mongolian Central Power System

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Abstract – This paper describes evaluation results of the wind power penetration limit (WPPL) and the wind energy penetration (WEP) in the Mongolian central power system (MCPS). A wind power plant (WPP) in a power system possesses an output power limit because the power system must maintain a balance between the generation and consumption of electricity at all times in order to achieve an adequate level of quality. The instantaneous penetration limit (IPL) of wind generation at a load is determined as the minimum of the three technical constraints: the minimum output, the ramp rate capability, and the spinning reserve of the conventional generating units. In this paper, a WPPL is defined as the maximum IPL divided by the peak load. A maximal variation rate (VR) of wind power is a major factor in determining the IPL, WPPL, and WEP. This paper analyzes the effects of the maximal VR of wind power on the WPPL, WEP, and capacity factor (CF) in the MCPS. The results indicate that a small VR can facilitate a large amount of wind energy while maintaining a high CF with increased wind power penetration.

Keywords: Instantaneous penetration limit, Wind energy penetration, Wind power penetration limit, Maximal variation rate of wind power, Capacity factor

1. Introduction

Wind generation has achieved grid parity over the last decade because of its technical advances and financial viability. In fact, many countries regard wind energy as an enabler of energy security as well as a pathway for reducing greenhouse gases. Moreover, the global installed capacity of wind power has increased significantly to 199 GW as of 2010 and is expected to increase to 832 GW by 2020 [1].

To achieve these goals, the Parliament of Mongolia approved the National Renewable Energy Program in 2005 and the Renewable Energy Law in 2007. The National Renewable Energy Program started in June 2005 to promote the development of renewable energy in Mongolia and will take effect throughout the period of 2005~2020. Under this program, the percentage share of renewable energy in the total electrical energy production is set to reach 20~25% by 2020 [2]. In addition, the Renewable Energy Law was passed in January 2007 to regulate the generation and supply of energy utilizing renewable energy sources.

According to the wind energy resource *Atlas of Mongolia*, the possible energy output of wind energy resources is 8,100 TWh per year and the corresponding installed capacity is 4,300 GW [3]. In Mongolia, the current total installed capacity of wind power plants (WPPs) is very small, and the installed capacity of wind-solar-diesel hybrid stations is 3.8 MW. However, a WPP with a capacity of 50 MW is being constructed in 2012, and another WPP with a capacity of 290 MW will be constructed by 2020 [2]. Both of these plants will be interconnected to the Mongolian central power system (MCPS). Note that the total installed capacity of these new plants (340 MW) is 22.7% of the peak load (1,500 MW in 2020) of the MCPS, which is so large that it can cause problems in the operation of the MCPS.

A power system must maintain a delicate balance between the generation and consumption of electricity at all times in order to ensure a stable frequency. Consequently, if a large WPP is connected to a power system, the power quality might diminish significantly due to the variability of wind power. Thus, the WPP has an output power limit, which plays a very important role in the reliable operation of a power system, as well as in the efficient operation of the WPP. Additionally, it is necessary to estimate the maximum capacity of the wind power, the wind energy production, and the wind generation capacity factor (CF) in order to maximize the efficiency.

Several studies on the output power limit of both wind generation and wind energy production in an island power system have been reported [4, 5]. Two criteria based on the technical minimum output of thermal power units and the dynamic penetration limit factor were suggested to evaluate power limitations and energy yield in an island power system [4]. Likewise, three criteria based on the

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technical minimum, the ramp rate, and the dynamic penetration limit factor were applied to Jeju Island in Korea [5]. However, the generator configuration for an island power system is different than that for an inland system and is unique for most countries. In addition, it is difficult to quantitatively analyze influence of the dynamic penetration limit factor used in [4, 5] on the power system operation.

On the other hand, when a large scale WPP is connected to a power system, the output of wind generation gives adverse influences on the stability of a power system due to its inherent variability. Thus, the impacts of large scale wind energy integration on the stability of a power system [6-8] were investigated. In addition, some compensation methods were suggested to enhance the system stability as well. However, the stability issues are different from the issue of the wind power penetration limit (WPPL) in a power system. This means that the WPPL is the necessity condition to accept the wind generation from the view point of the overall power system operation.

In this paper, an instantaneous penetration limit (IPL) of wind generation at a load is determined to be the minimum of the three technical constraints – the minimum output, the ramp rate capability, and the spinning reserve of the conventional generating units. Moreover, this paper divides the dynamic penetration limit factor from [4, 5] into the two factors – the ramp rate and spinning reserve – in order to analyze the wind generation output limit quantitatively. Note that the WPPL is defined as the maximum IPL divided by the peak load, and the VR is a dominant factor in the IPL, WPPL, and WEP. Thus, this paper analyzes the effects of the wind power VR on the WPPL, WEP, and CF in the MCPS.

2. The IPL, WPPL, and WEP of a power system

As mentioned, a power system must maintain a precise balance between the generation and consumption of electricity in order to prevent gross frequency deviations from the nominal value. Unfortunately, a WPP is unable to provide electricity with sufficient quality and reliability due to the variability of wind. Hence, in order to maintain adequate quality and reliability, WPPs should operate in conjunction with conventional power plants; then, the sum of their outputs can meet the instantaneous load requirements at all times. In other words, wind generation has an output power limit. In this section, we define the IPL of a power system, which depends on three criteria, and then we discuss the WPPL and WEP of a power system and the CF of wind generation.

2.1 The IPL and the WPPL

To maintain the balance between the generation and consumption in a power system, the output power limit of wind generation depends on the operating constraints of the conventional generating units. These constraints can be divided into the three types: the minimum output (criterion 1), the ramp rate capability (criterion 2), and the spinning reserve (criterion 3) of the conventional generating units.

2.1.1 Minimum output (criterion 1)

To avoid life-shortening of a prime mover, a thermal generating unit should not be operated below the threshold of its rated power, which is referred to as the ‘technical minimum’. Thus, the maximum output of wind generation that can maintain the balance between the generation and consumption can be determined by

$$P_{W\max}^{T} = P_L - \sum c_T * P_{Dn} \tag{1}$$

where P_L is the power system load, c_T is the technical minimum factor, and P_{Dn} is the rated power of the operating generator. Typical values of c_T are 30–50% for heavy oil units and 20~35% diesel fired units (including gas turbine), depending on the age and overall condition of the engine [4].

2.1.2 Ramp rate capability (criterion 2)

Recall that a power system must maintain the balance between the generation and consumption to ensure quality even when the output power of wind generation fluctuates. Consequently, the output of wind generation is acceptable as long as the conventional generating units can compensate for the wind generation variation rate. Thus, the maximum output of wind generation depends on the ramp rate of the conventional generating units and can be expressed by

$$P_{W\max}^{RR} = \frac{\sum RR_G}{VR_{wind}} \tag{2}$$

where RR_G is the ramp rate of a conventional generating unit, and VR_{Wind} is the maximum variation rate of wind generation.

2.1.3 Spinning reserve (criterion 3)

The wind can disappear unexpectedly, causing the frequency of a power system to decrease unless there is a sufficient spinning reserve that can cope with a sudden loss of wind.

A power system does not accept the wind power more than spinning reserve of the conventional units to ensure reliability even when the wind disappears suddenly.

Thus, the maximum output of wind generation can be expressed as

$$P_{W\max}^{SR} = \sum P_{Dn} - P_D - P_S \tag{3}$$

where P_D is the output power, and P_S is the spinning reserve for a load.

2.1.4 The IPL of a power system at a load

Finally, the IPL of a power system can be defined by the minimum of the three criteria of (1)~(3) and expressed as

$$IPL = \min\left\{P_{W\max}^{T}, P_{W\max}^{RR}, P_{W\max}^{SR}\right\}. \tag{4}$$

Clearly, the IPL of a power system depends on the system load and typically increases with that load.

2.1.5 The WPPL of a power system

In this paper, the WPPL is defined as the maximum IPL divided by the peak load and can be expressed by

$$WPPL = \frac{\max(P_{W\max})}{\max(P_L)} * 100\%. \tag{5}$$

The WPPL is the maximum value of wind power that a power system can accept while the IPL varies with a load. Thus, the WPPL is useful for determining the suitable installed capacity in a power system.

2.2 WEP of a power system

To determine the annual wind energy production of a power system, it is necessary to obtain certain information, such as the power characteristics of the wind turbine (cut-in speed, cut-out speed, and rated speed) and the discrete distribution of the wind speed and load statistics. Note that the WEP is defined as the annual wind energy production divided by the total electrical energy output of a power system.

2.2.1 Annual wind energy production

Energy production of a WPP depends on wind speed and load demand, which random variables and can be assumed to be statistically independent. The annual wind energy production can then be expressed by

$$E_{Wk} = 8760 \sum_{i=1}^{N_V} \sum_{j=1}^{N_L} H_i F_j P_{Wk}(V_i, P_{Lj}) \tag{6}$$

where H_i is the discrete probability distribution of wind speed in bin i, F_j is the usage time of each load in bin j, N_v and N_L are the numbers of wind speed values and load bins, respectively, and V and P_L are random variables representing the wind speed and the load, respectively. In addition, $P_{Wk}(V, P_L) = \min\{P_{PC}(V), P_{W\max}(P_L)\}$, where $P_{PC}(V)$ is the power curve output and $P_{W\max}(P_L)$ is the output limit due to power system restriction.

2.2.2 WEP of a power system and CF of a WPP

WEP is a percentage of electrical energy that is supplied from a WPP and can be expressed by

$$WEP = \frac{E_{Wk}}{E_{Load}} * 100\% \tag{7}$$

where E_{Load} is the energy of a load demand.

The utilization of a WPP can be measured by a CF, which is defined by the ratio of the amount of energy generated by a unit to the maximum amount of the unit; i.e.,

$$CF = \frac{E_{Wk}}{T \times P_{Wn}} * 100\% \tag{8}$$

where P_{Wn} is the wind turbine or WPP rated power and T is the number of hours in a year (8760 hours). The CF is the most important factor for determining the feasibility of WPP investments.

3. Evaluations of the WPPL and WEP in the MCPS

The annual load statistics in 2011 and generator characteristics of the MCPS were reported in [9, 10]. Note that the Mongolian energy sector consists of four power systems: 1) A central power system (CPS) that has five coal-fired thermal power plants – TPP4, TPP3, TPP2, “Darkhan” TPP and “Erdenet” TPP – and is interconnected with a Russian energy system. The CPS meets the energy demand of Ulaanbaatar city and 14 provinces. Fig. 1 shows the configuration of the MCPS. 2) A western power system that is interconnected with a Russian energy system using the “Durgun” hydro power plant (12 MW) and meets the energy demand of three provinces. 3) An eastern power system that has a coal-fired thermal power plant and supplies energy to two provinces. 4) The “Altai-Uliastai” system that has six hydro power plants (14 MW total) and diesel generators and that provides energy to two provinces.

Among them, the MCPS is the largest power system in Mongolia; thus, the planned WPPs will be interconnected to the MCPS. In this section, we evaluate the IPL, WPPL, and WEP of the MCPS, and we analyze the effects of the wind power VR on the WPPL, WEP, and CF in the MCPS.

3.1 Information on the MCPS and wind

The evaluation methodology requires the following basic information: the annual load statistics of the power system, the technical characteristics of the conventional generators, the wind speed distributions at the WPP installation site, and the power curve of a wind turbine.

3.1.1 Annual load statistics of the MCPS

In this paper, the annual load statistics of the MCPS for 2011 were used. The peak and base loads of the MCPS were 769.78 MW and 255.3 MW, respectively, and total energy of the MCPS was 4.45 TWh [9].

Fig. 2 shows the load statistics of the MCPS derived from one hour of data. The discrete probability distribution of the load (20 MW bin width) and the load duration curve are illustrated in Figs. 2a and 2b, respectively. During the peak load in 2011, the electricity imported from the Russian power system for the MCPS was 200.6 GWh.

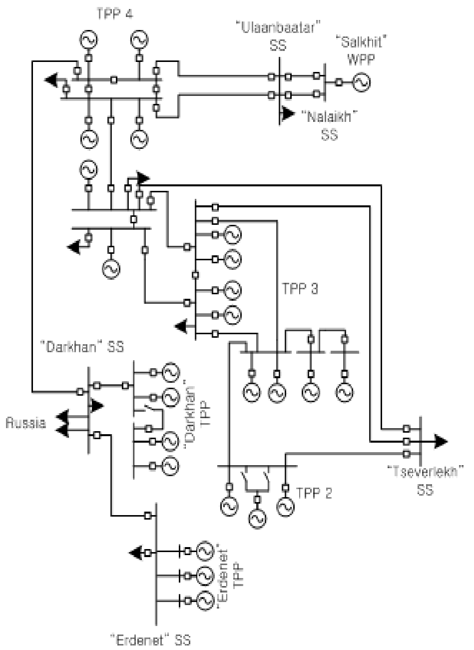
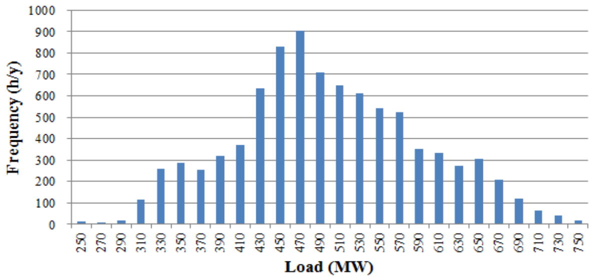
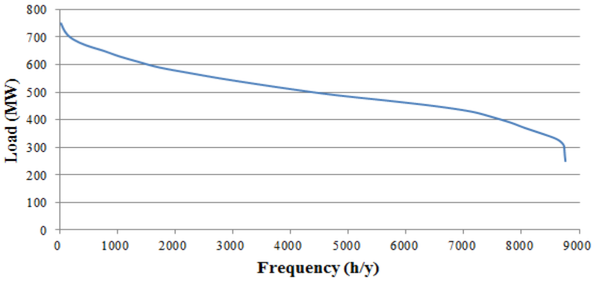


Fig. 1. Configuration of the MCPS



(a) Probability distribution of annual load



(b) Load duration curve

Fig. 2. Characteristics of a Mongolian power system load

3.1.2 Technical characteristics of the conventional generators

In the MCPS, there are five coal-fired thermal power plants (TPPs), which consist of 24 thermal power generators. Table 1 shows the technical data (model, installed capacity, and ramp rate) of these generators. The total installed capacity of the MCPS is 826.3 MW and spinning reserves are 92 MW in winter and 12 MW in spring, summer, and autumn.

Note that the ramp rates of the coal-fired generators in the MCPS are 10~20% per minute, which are higher than those of typical coal-fired generators (i.e., 5~10% per minute).

Table 1. Technical data for the generators in the MCPS

Unit	Model of generator	Installed capacity (MW)	Number of generators	Ramp rate (%/min)
TPP-4	T-100-130	100	5	10
	ПТ-80-130	80	1	18.5
TPP-3	ПТ-25-90/10M	25	4	10
	ПТ-12-35/10M	12	4	20
Darkhan TPP	ПТ-12-35/10M	12	4	20
TPP-2	ПТ-12-35/10M	12	1	20
	AK-6-35	5	1	20
	P-4-35	3.5	1	20
Erdenet TPP	ПТ-12-35/10M	12	1	20
	P-12-35/6	12	1	20
	P-4,8-35	4.8	1	20
Total		826.3	24	

3.1.3 Data on the MCPS wind and wind turbines

The measured wind speed data and other information of the "Salkhit" WPP were reported in [11]. In Mongolia, a 50 MW WPP is being built and will be interconnected to the MCPS in 2012. The installed capacity of the WPP is expected to reach 250 MW by 2015 and about 1,000 MW by 2025 [11].

The "Salkhit" WPP will be connected to the "Nalaih" substation of the MCPS by 25 km of 110 kV transmission

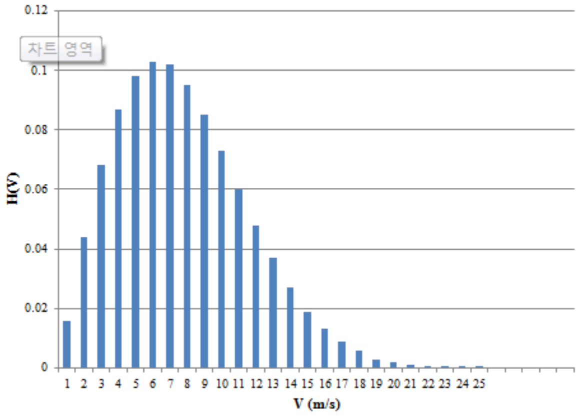


Fig. 3. Wind speed distribution

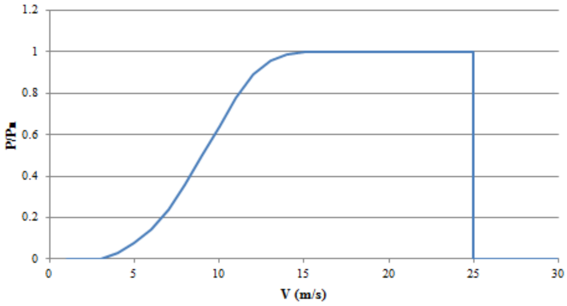


Fig. 4. Power curve of a wind turbine

line. The “Salkhit” WPP consists of 31 wind turbines producing 1.6 MW of power each, with a total installed capacity of 49.6 MW. The average wind speed in this region is 7.8 m/s. The wind speed distribution and the power curve of a wind turbine are shown in Figs. 3 and 4, respectively [11]. In Fig. 4, the cut-in speed, rated speed, and cut-out speed of the studied wind turbine are 4 m/s, 15 m/s, and 25 m/s, respectively.

3.2 The IPL and WPPL in the MCPS

The IPLs and WPPLs in the MCPS were investigated by varying the VR from 70% to 40%. Fig. 5 shows the estimated results, where c_T is set to be 50% in this paper. Note that, among the three criteria, criteria 1 and 3 remained unchanged, while only criterion 2 changed when varying the VR. Fig. 5a shows the results for a VR of 70%, where $P(RR)_{Wmax}$ is lower than the other two criteria except for loads less than 350 MW. In this case, the MCPS WPPL from (5) is 28.44%.

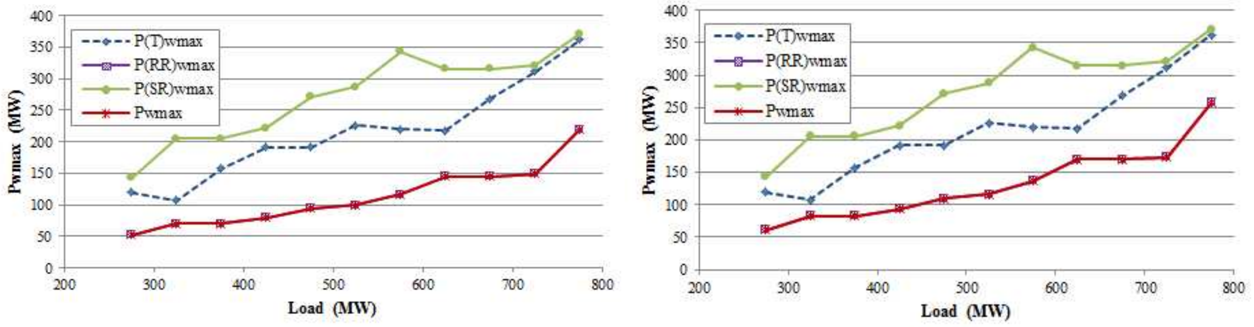
Table 2. WPPLs for VRs of 70%, 60%, 50%, and 40%

VR (%)	70	60	50	40
WPPL (%)	28.44	33.17	39.81	46.69

For the VR of 60%, the results are the similar to that of the VR of 70%. However, for the VR of 40%, as shown in Fig. 5d, $P(T)_{Wmax}$ is the dominant factor for determining the IPL because it is lower than the other two criteria, except for loads larger than 650 MW. Fig. 6 shows the IPLs for various VRs. We can see that the IPLs increased significantly during the peak loads because electricity was imported from the Russian power system during those peak times, as mentioned in Section 3.1. Table 2 shows the WPPLs for various VRs from 70% to 40%. The results clearly indicate that the WPPL increased as the VR decreased.

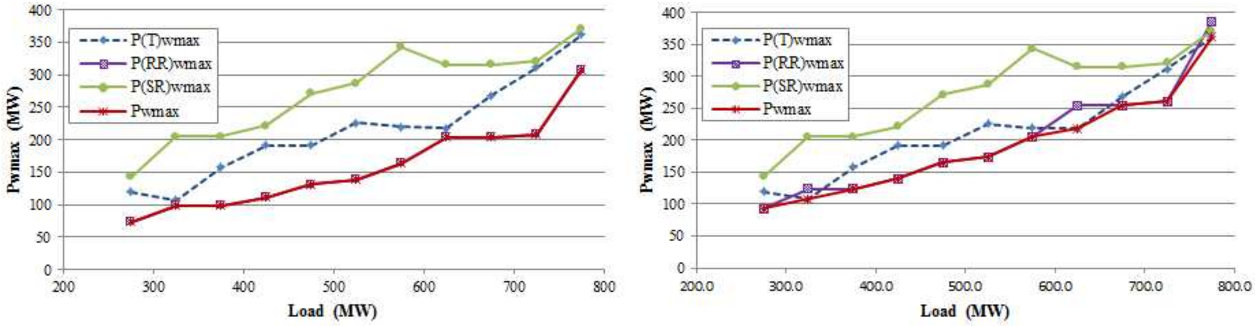
3.3 The WEP and CF in the MCPS

Fig. 7 shows WEP found via (6) and (7) for VRs of 70%, 60%, 50%, and 40% per minute when the installed capacity of wind generation ranged from 5% to 50% of the peak load. In the MCPS, the amount of wind energy is the same for all the VRs, assuming the installed capacity is increased only up to 10%. However, above 10%, the amount of wind



(a) For a VR of 70%

(b) For a VR of 60%



(c) For a VR of 50%

(d) For a VR of 40%

Fig. 5. Three criteria and the IPLs for various VRs

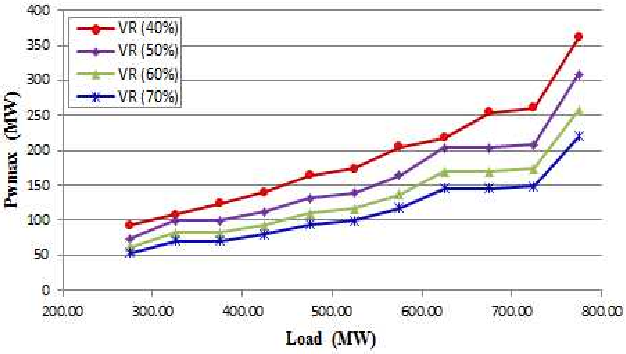


Fig. 6. IPLs for VRs of 70%, 60%, 50%, and 40%

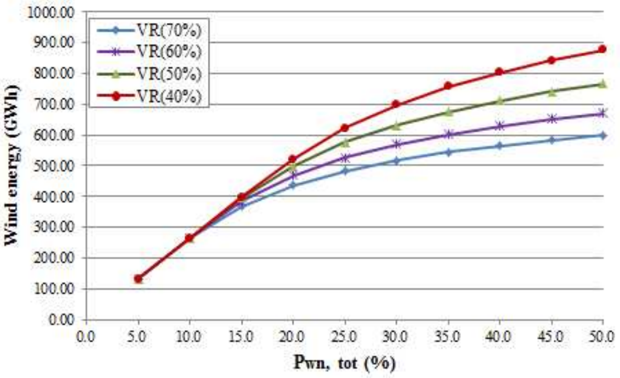


Fig. 7. WEP for the installed capacity of wind generation

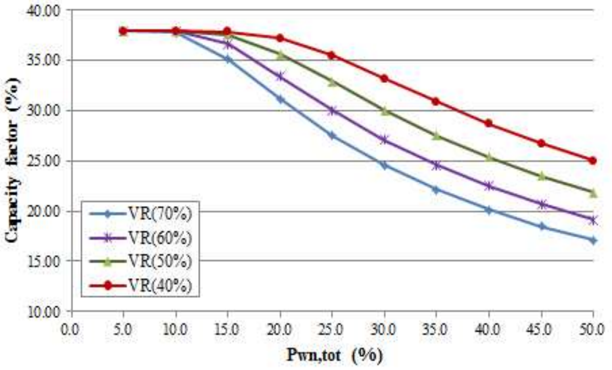


Fig. 8. CF for the installed capacity of wind generation

energy for a small VR is larger than that for a large VR. For example, if the installed capacity is 50%, wind energy for a VR of 40% is 875 GWh, which is 146% of the wind energy for a VR of 70% (600 GWh).

Fig. 8 shows the CFs using (8) when the installed capacity of wind generation ranges from 5% of the peak load to 50% of the peak load. Generally, the CF decreases when the installed capacity increases; this pattern is evident in Fig. 8 for the MCPS. If the installed capacity is less than 10%, the difference between a high VR and a low VR is negligible.

However, as the installed capacity grows, the difference increases. For example, in the case of the 25% installed capacity, the CF for a 70% VR is 28%. On the other hand, the CF for a 40% VR is 35%, which is 128% of a 70% VR. This means the income for a 40% VR is 128% higher than that of a 70% VR. These results indicate that a small VR can produce a large amount of wind energy while maintaining a high CF.

4. Conclusion

This paper evaluated the IPL, WPPL, and WEP of the MCPS and analyzed the effects the wind generation VR on the MCPS WPPL and WEP, as well as on the CF of wind generation. In this paper, three criteria of the minimum output, the ramp rate capability, and the spinning reserve were used to evaluate the wind generation output limit quantitatively.

Among the many factors affecting wind power production, the maximal wind generation VR is a major factor for determining the IPL, WPPL, WEP, and CF. The result indicate that a small VR can produce a large amount of wind energy while maintaining a high CF when the installed capacity of wind generation increases. Consequently, by minimizing the maximal VR, we can achieve the most efficient wind energy.

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