

A New AC/DC Converter for the Interconnections between Wind Farms and HVDC Transmission Lines

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Abstract

In this paper, a new ac/dc converter is proposed for HVDC-connected wind farms. The proposed converter provides a suitable dc voltage for HVDC transmission systems. Each wind turbine is connected to two full bridge diode rectifiers. These rectifiers are connected to each other by three thyristors. Firing the thyristors at desired angles provides an adjustable dc voltage in the output of the converter. Simulation results show the efficiency of the proposed converter.

Key words: AC/DC converter, HVDC, Rectifier, Wind farm, Wind turbine

I. INTRODUCTION

In recent years, due to the reduction of energy resources and environmental problems, the application of renewable energy sources has substantially increased. Among these sources, wind energy has matured to a high level of development.

Wind turbines are usually operated in the form of wind farms to increase the power obtained from the wind. Wind farms may be located onshore or offshore. Recently, offshore wind farms have become more interesting in comparison with onshore ones. This lack of suitable sites for onshore farms, and the high wind power, as well as the relatively fixed wind speed, in offshore farms [1]. However, offshore wind farms are challenging with the long distances to consumers. Therefore, their generated power should be transferred through HVAC or HVDC transmission lines. In this case, HVDC transmission is the preferred option, since it has more appropriate features, when compared with HVAC, for power transfer through long transmission lines [2]. HVDC converters are mainly divided into current source converters (CSC), which is called line commutated converters (LCC), and voltage source converters (VSC). CSC-based transmission is the most widely used type of HVDC transmission and is available for high levels of power transfer capacity. This capacity is provided for CSC by the means of

high power thyristors. On the other hand, VSC-based transmission applies power electronics switches with the capability to turn-off, such as IGBTs. Because of the IGBT ratings, the VSC's power transfer capacity is lower than CSC. In addition, the VSC requires a commutation circuit [3]-[5].

Wind energy converters mainly consist of turbines and generators. In practice, most types of generators are doubly fed induction generators (DFIG), squirrel cage induction generators (SCIG), and permanent magnet synchronous generators (PMSG). Among these, the DFIG and PMSG can be applied in variable wind speeds, while the SCIG is used where the wind speed is fixed [6]. In the PMSG, since the generator speed is low, no gearbox is needed. This is worthwhile since the maintenance of gearboxes requires a lot of cost and time [7]. Moreover, the PMSG has a large air gap and is excited by permanent magnets. Hence, the value of flux linkage in PMSG is relatively small, which allows the generator to have a small size [8, 9]. In a general view, some features such as low losses, small size, high reliability, and no gearbox requirement, makes the PMSG the best option for application to wind energy conversion at low power rates and in offshore wind farms. Nevertheless, to have a large amount of torque, the turbine's diameter should be enlarged. In addition, to have an adequate frequency at low speeds, the number of generator poles should be increased [10].

In conventional wind energy applications, the generated voltage of the wind farms is first rectified using an ac to dc converter. Afterwards, the output dc power is transferred to the load centers via HVDC transmission lines. At the end point, the dc power is converted into ac using dc to ac inverters. In this system, the rectifier controls the generator's

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speed and torque. To obtain the maximum power from the wind, the rectifier should be able to operate in an extensive range of wind speeds. Meanwhile, considering the large number of turbines in a wind farm and for the reduction of operating costs, the number of expensive power electronic switches, which are used in the rectifier, should be reduced as much as possible.

There are many proposed structures in the literature for ac to dc converters, such as PWM rectifiers, uncontrolled diode rectifiers, applying a dc chopper to the rectifier, and the application of a diode rectifier with a variable-speed turbine. However, all of the mentioned structures, when they are applied in a wide range of wind speeds, experience one of the following problems: complication of the control system and the machine windings, increasing of the size of the grid side inverter, and growth of the operation costs.

In [11], a new structure is proposed for the rectifiers used in wind energy conversion systems. In this structure, the PMSG has dual stator windings. These two windings are reconfigured so that two voltage sources with equal magnitudes and a 180° phase difference are provided. By the means of two diode rectifiers and three thyristors, the mentioned stator windings can be connected in series or in parallel to each other. In [11], by controlling the firing angles of the thyristors, the output dc voltage varies between 1 and 2 pu. In this paper, this structure is developed for applying in the wind farms. The proposed converter can provide the proper voltage level for HVDC transmission systems. Better conception, explanation and analysis of the performance of the proposed converter are presented with simulation results. All of the simulations are executed in PSCAD/EMTDC.

II. THE PROPOSED AC/DC CONVERTER

Fig. 1 shows the structure of the proposed ac/dc converter. This structure is used for wind farms which consists of n wind turbines leading to n generators and $2n$ neutral points. In this figure, each generator has two stator windings, which are modeled by two balanced three-phase voltage sources. These sources have the same magnitude and a 180° degree phase difference [11]. The two upper voltage sources are representatives of the stator windings of the first turbine, while the two lowest voltage sources denote the stator windings of the n th turbine. Each voltage source is connected to a full bridge diode rectifier. These rectifiers are connected to each other via three thyristor stages. Each stage consists of three thyristors as well.

For analysis of the performance of the proposed rectifier, it is connected to an R - L Load.

It should be noted that the neutral points of the voltage sources that are named by $\{N_1, N'_1\}$ for the first turbine, $\{N_2, N'_2\}$ for the second turbine, ..., $\{N_n, N'_n\}$ for the

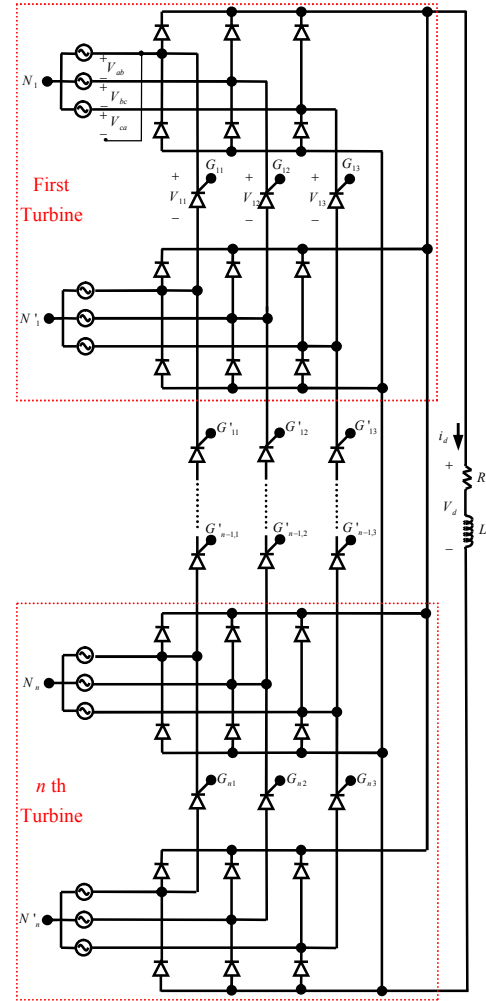


Fig. 1. Structure of the proposed ac/dc converter.

n th turbine; are not connected to each other.

III. SWITCHING PATTERN OF THE THYRISTORS

Due to the proper control of thyristors, the voltage sources can be connected in series or parallel to each other. To turn the thyristors on, the voltage of their anode to cathode should be positive and a positive pulse should be applied to their gates. Therefore, the voltage across the thyristors should be measured in order to know when they can be turned on. For example, the voltages across the thyristors of the first stage, assuming that they do not receive firing pulse, are shown in Fig. 2. From this figure, each thyristor has a positive voltage in every half-cycle, and a negative voltage, in the subsequent half-cycle. The thyristor pulses are indexed by two-digit numbers. The first digit denotes the number of the turbine and the second digit indicates number of the thyristor phase and the "prime symbol" is used for the thyristors between the turbines. For example, G_{12} indicates the pulse of the second phase thyristor between the first and second stages of the first turbine and G'_{12} indicates the pulse of the second

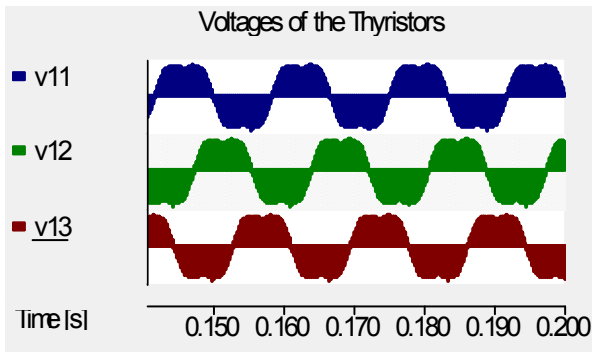


Fig. 2. Voltages of the first stage thyristors.

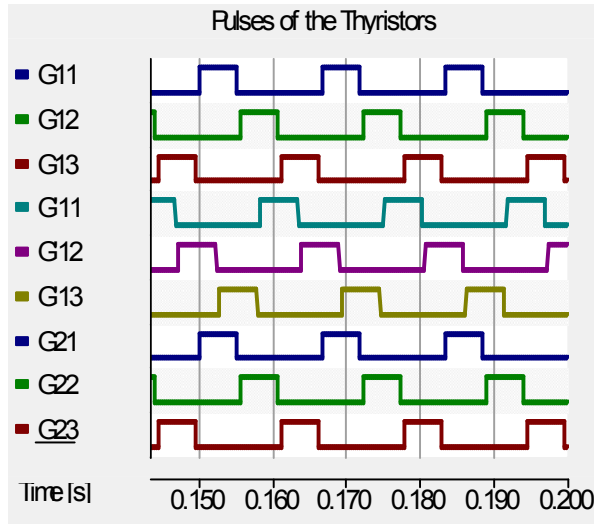


Fig. 3. Firing pulses of thyristors.

phase thyristor between the first and second turbine. Fig. 3 shows the firing (gate) pulses applied to the thyristors. These pulses are synchronized with their corresponding line-to-line voltages using phase locked loops (PLL).

For example, the firing pulses of G_{11} , G_{12} and G_{13} are synchronized with V_{ab} , V_{bc} and V_{ca} , respectively. As a result, there is a phase difference of 120° between these pulses.

The firing pulses of the second stage thyristors are 180° out of phase with those of the first stage thyristors, while the pulses of the third stage are in phase with the pulses of the first stage.

Generally, in each stage, there is a 120° phase shift between the firing pulses. In the main stages (1, 2 . . .), the firing pulses are synchronized with each other, while in the secondary stages (1', 2', ...), they are synchronized with each other and are delayed by 180° from the firing pulses of the odd stages.

IV. SIMULATION RESULTS FOR A WIND FARM WITH TWO TURBINES

Fig. 4 shows the structure of the proposed ac/dc converter

for a wind farm which consists of two wind turbines. However, it can be developed for desired number of wind turbines. In this case, there are two PMS generators and four stator windings which are shown with four balanced three-phase voltage sources, four simple uncontrolled three-phase bridge rectifiers and nine thyristors, in total. In this simulation, the rated line to line voltage of the generators is 64 V, and the rectifier is connected to a simple R-L load with a time constant of 4 msec. In addition, to illustrate the performance of the rectifier, it is assumed that a wind speed drop takes place in the steady state of the system. A time duration of 50 msec is shown for the simulation results in Figs. 6 and 7.

A. Output Voltage of the Rectifier

Fig. 5 represents the output voltage of the proposed ac/dc converter in a wind farm which consists of two wind turbines. Different firing angles are considered in this figure. In this simulation, the line to line terminal voltage for each stator winding of the generators is 64 v. Depending on the firing pulse of the thyristors, it can increase to 128 v for one generator and to 256 V for the wind farm of two turbines. It should be noted that a wind speed drop takes place at 0.16 seconds. As a result, a voltage drop comes about at this time, and depending on the dynamic response of the rotor and the generator inertia, after a moment, the new magnitude of the voltage stands at 46% of the pervious value.

In this topology, each thyristor has the maximum voltage in one third of a cycle (120°). The firing angle of each thyristor can be set between 0° to 150° . For $0^\circ \leq \alpha < 30^\circ$, each thyristor conducts for 120° in one cycle, and is turned off as the following thyristor is fired. For $30^\circ \leq \alpha \leq 150^\circ$, each thyristor conducts for $(150 - \alpha)^\circ$ in one cycle, and commutates by the voltage source [11].

Assuming that the wind farm consists of two wind turbines, Fig. 6 represents the output voltage of the proposed converter for $\alpha = 0^\circ$ and 150° including wind speed variations. Using this figure, the output dc voltage can be computed. Each cycle consists of six time intervals of 60 degrees. The total dc voltage can be calculated by averaging the output voltage during the one of these time intervals. The intervals are determined by the dotted lines in Fig. 6. Before a wind speed variation, the output dc voltage (V_d) for the two different firing angles and the ripple factor (RF) are computed in the Appendix.

For $\alpha = 0^\circ$, the thyristors of the first and third stages are turned on in the whole cycle, while the thyristors of the second stage are turned off during the whole cycle. Considering Fig. 6(a), v_{ab} is the line to line voltage of the first voltage source. In this situation, the output voltage may be equal to four times v_{ab} .

TABLE I
SPECIFICATION OF THE PROPOSED CONVERTER

Number of turbines	2	n
Number of 3ph sources	4	$2n$
Number of thyristors	9	$6n - 3$
Number of diodes	24	$12n$
DC voltage variations (pu)	$\frac{12}{\pi} - \frac{3}{\pi}$	$\frac{6n}{\pi} - \frac{3}{\pi}$

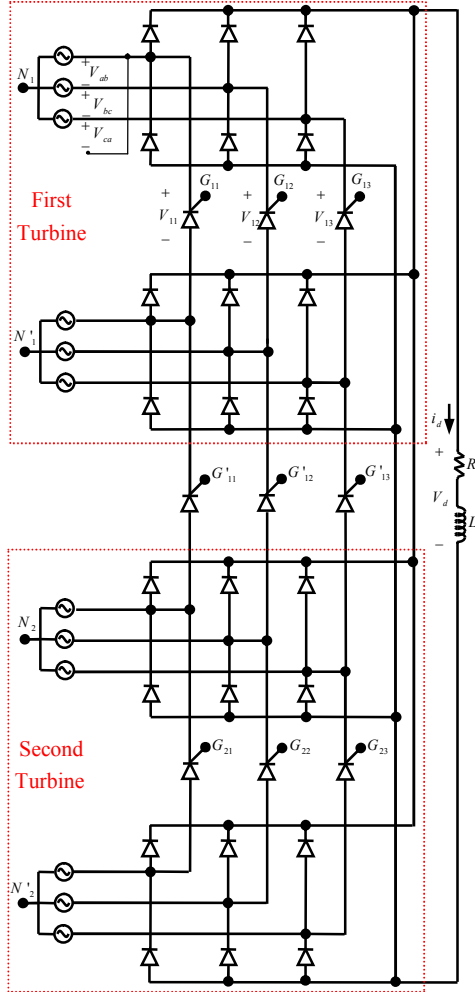
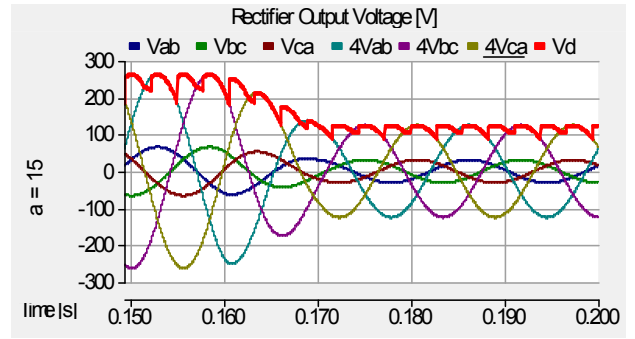


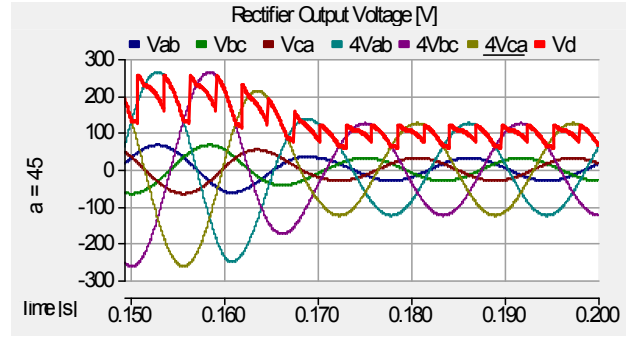
Fig. 4. The proposed ac/dc converter for two wind turbines.

Considering Fig. 6(b), the output voltage is equal to v_{ab} . V_{ab} is the magnitude of v_{ab} . Assuming this value as the base voltage, V_d becomes equal to $12/\pi$ pu and $3/\pi$ pu for $\alpha = 0^\circ$ and 150° , respectively.

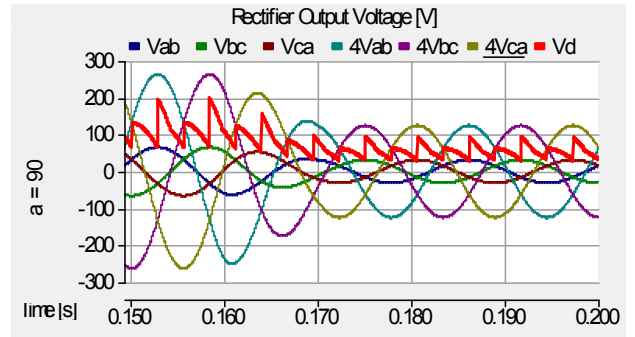
In general, for a wind farm with n wind turbines, the output voltage varies between 1 to $2n$ times the line to line voltage. Similarly, it can be shown that the output dc voltage varies between $3/\pi$ pu and $6n/\pi$ pu. Table I presents the specifications of the proposed method for the application of two and n turbine wind farms.



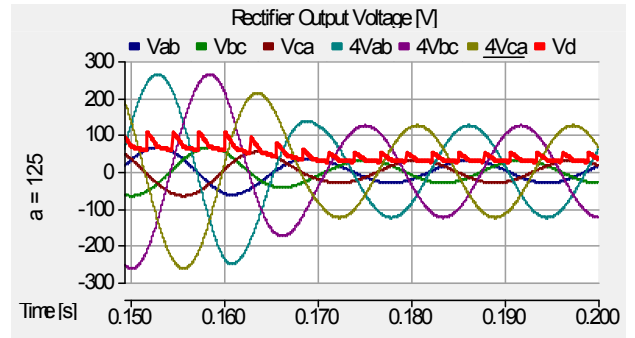
(a) $\alpha = 15^\circ$.



(b) $\alpha = 45^\circ$.



(c) $\alpha = 90^\circ$.



(d) $\alpha = 125^\circ$.

Fig. 5. Output dc voltage of the proposed converter in a wind farm of two turbines.

B. Output Current of the Rectifier

Fig. 7 represents the output current of the proposed ac/dc converter in a wind farm which consists of two wind turbines. Different firing angles are considered in this figure. The

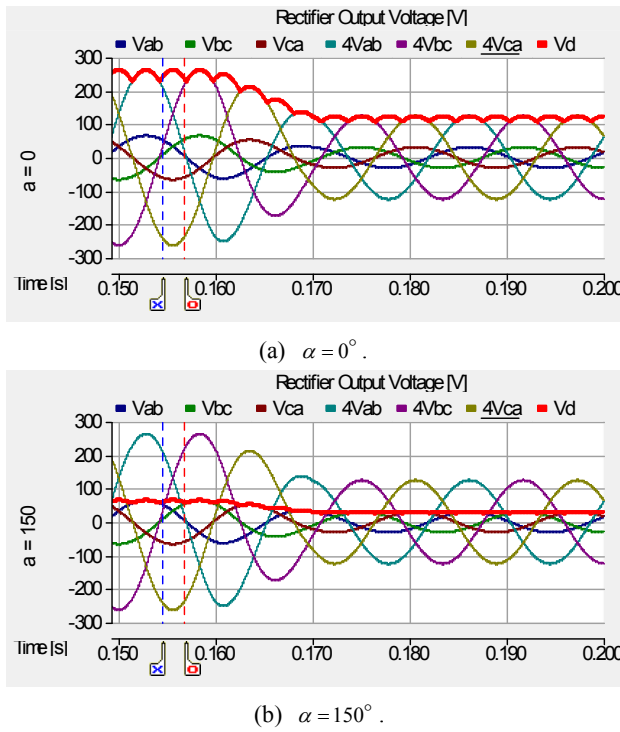
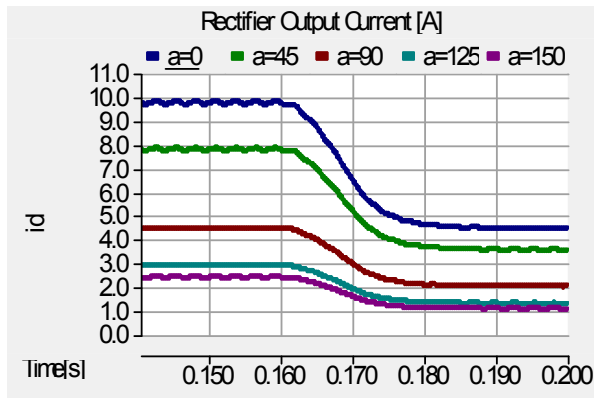


Fig. 6. Output DC voltage of the proposed converter.

Fig. 7. Output current of the proposed converter in a wind farm of two turbines; for $\alpha = 0^\circ$; $\alpha = 45^\circ$; $\alpha = 90^\circ$; $\alpha = 125^\circ$; $\alpha = 150^\circ$

rectifier has an R-L load with a time constant of 4 ms so that the output current rises from zero and leads to a specific value. This treatment of the current is due to the fact that an inductance element is short-circuited in the steady state condition of the DC circuits. This condition guaranties the stability of system. However, in this figure, only the steady state of the system process can be shown. In addition, a wind speed drop at time 0.16 s leads to voltage and current drop in the rectifier output. According to Fig. 7, in several firing angles, a current decrease comes about at this time and the output current of the rectifier, depending on the circuit time constant value and how the voltage value decreases, stabilizes at specific lower level, after a moment.

V. CONCLUSIONS

The proposed ac/dc converter is capable of increasing the output voltage of wind farms for power transfer through HVDC transmission lines. Since a series connection of input voltage sources can be provided by the proposed converter, it can deliver the maximum power under different wind speeds. Therefore, the proposed converters do not need to increase the rating of the AC side inverters or the pole-changing wind turbine generators. For each turbine, the application of two stator windings can be easily achieved by the proper connection of the stator windings. This costs a lot less than the application of pole-changing wind turbine generators. Moreover, because of the boost capability of the proposed converter, there is no need to apply a DC chopper. Meanwhile, commutation circuits are not required because the converter is line commutated. These cost savings for a single turbine are repeated for the other turbines when the number of stages is increased and this is the main reason for its cost-effectiveness. This means that the proposed AC-DC converter has a simple, low cost and effective structure, which makes it competent for practical applications. From the equations in the Appendix section, it can be seen that in comparison with the proposed rectifier for a single turbine, use of the rectifier for a wind farm of "n" turbines leads to increases and decreases in the dc voltage and Ripple Factor (R.F). In addition, one of the advantages of the proposed rectifier is its low R.F. in comparison with similar rectifiers such as half and full wave 3 phase diode rectifiers which have an R.F of 18.3 % and 4.2 %, respectively.

APPENDIX

A. Computation of the Output dc Voltage

Fig. 6 represents the output voltage of the proposed converter for 0° and 150° so that the output dc voltage (V_d) for the two different firing angles and for a wind farm of n turbines can be computed as follows:

(The change of the wind speed is neglected)

For $\alpha = 0^\circ$:

$$V_{dc} = \frac{1}{\pi/3} \int_{-\pi/6}^{\pi/6} (2n)v_{bc}(\omega t)d(\omega t) = \frac{6n}{\pi}V_{bc} \quad (1)$$

For $\alpha = 150^\circ$:

$$V_{dc} = \frac{1}{\pi/3} \int_{-\pi/6}^{\pi/6} v_{bc}(\omega t)d(\omega t) = \frac{3}{\pi}V_{bc} \quad (2)$$

In (1) and (2), V_{bc} is the magnitude of v_{bc} . Assuming this value as the base voltage, V_d becomes equal to $6n/\pi$ pu and $3/\pi$ pu for $\alpha = 0^\circ$ and 150° , respectively.

B. Computation of the Ripple Factor of the Rectifier

In this section, the ripple factor of the proposed rectifier (R.F.) is computed for firing angles of 0° and 150° . (The change of the wind speed is neglected).

For $\alpha = 0^\circ$:

$$V_{rms} = \left(\frac{2n}{\pi/3} \int_{-\pi/6}^{\pi/6} v_{bc}^2(\omega t) d(\omega t) \right)^{\frac{1}{2}} = (1.9115n)V_{bc} \quad (3)$$

$$V_r = \sqrt{V_{rms}^2 - V_{dc}^2} = (0.0782n)V_{bc} \quad (4)$$

$$R.F. = \frac{V_r}{V_{dc}} = 4.09\% \quad (5)$$

For $\alpha = 150^\circ$:

$$V_{rms} = \left(\frac{1}{\pi/3} \int_{-\pi/6}^{\pi/6} v_{bc}^2(\omega t) d(\omega t) \right)^{\frac{1}{2}} = 0.9558V_{bc} \quad (6)$$

$$V_r = \sqrt{V_{rms}^2 - V_{dc}^2} = 0.0415V_{bc} \quad (7)$$

$$R.F. = \frac{V_r}{V_{dc}} = 4.35\% \quad (8)$$

From these equations, it is understood that the R.F. parameter for a wind farm of "n" turbines is less than that from a single turbine.

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