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Increasing an expected power of the wind farm with diversification in non-dominated power curves of the used wind turbines

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A problem of increasing an expected power of the wind farm is considered. Instead of a wind farm consisting of identical wind turbines, a wind farm is suggested to be built of a definite number of wind turbines having different power curves. A prime condition for those wind turbines is that their power curves should not dominate each other. Another constraint, inserted by default, is that total nominal powers of such wind farm and the farm of identical turbines must be equal. The gain increases when approaching to a cut-in speed. It increases slower for greater number of wind turbines.

Key words: *renewable energy, wind turbine, wind farm.*

Розглядається задача збільшення очікуваної потужності вітрової електростанції. Замість вітрової станції, що складається з однакових вітрогенераторів, пропонується будувати станцію з визначеного числа вітрогенераторів, котрі мають різні криві потужності. Вихідною умовою для цих генераторів є те, щоб їх криві потужності не домінували одна одну. Іншим обмеженням за умовчанням є те, що загальні номінальні потужності такої електростанції та станції з однакових генераторів мають бути рівними. Виграш збільшується з наближенням до швидкості включення. Він збільшується повільніше для більшого числа вітрогенераторів.

Ключові слова: *відновлювана енергетика, вітрогенератор, вітрова електростанція.*

Рассматривается задача увеличения ожидаемой мощности ветровой электростанции. Вместо ветровой станции, что состоит из одинаковых ветрогенераторов, предлагается строить станцию из определённого числа генераторов, которые обладают различными кривыми мощности. Исходным условием для этих генераторов является то, что их кривые мощности не должны доминировать друг друга. Другим ограничением по умолчанию является то, что общие номинальные мощности такой электростанции и станции из одинаковых генераторов должны быть равными. Выигрыш увеличивается при приближении к скорости включения. Он увеличивается медленнее для большего числа ветрогенераторов.

Ключевые слова: *возобновляемая энергия, ветрогенератор, ветряная электростанция.*

A problem of increasing wind power efficiency (WPE) for large grid systems

Wind power is a very good renewable energy source. Its effects on the environment are far less problematic than those of nonrenewable power sources. Wind farms (WFs) consist of many individual wind turbines (WTs) which are connected to the electric power transmission network [1, 2]. A challenge is the full integration into power grids (the combined transmission and distribution networks). Small WFs can feed just some energy into the grid or provide electric power to isolated off-grid locations [1, 3, 4]. Larger grid areas require not only larger WFs and more powerful WTs, but also higher stability of the generated electric power [4, 5]. It is hard to increase WPE for large grid systems considerably due to a lot of technical and economical obstacles [1, 2, 6].

Methods of meeting wind statistics in order to increase WPE

Some works (e. g., [5, 7]) suggest to improve WPE by a kind of diversification either in construction of WT or in deploying the WF. A novel pitch control method that integrates a non-standard extended Kalman-filter-based estimator is proposed in [5], wherein a cascade control structure is developed for the pitch controller, which receives the speed reference from a power-speed scheduler. Nonlinearities in the WT are removed with using the information provided by the estimator. The controller provides a consistent optimal performance under the global-power regulation while avoiding wind measurement. This method seems effective, if disregard costs of its implementation. The paper [7] proposes a micro-siting strategy that optimizes the layout of different farm areas synchronously for the largest profit of the whole WF. However, the produced energy of the WF designed by the proposed strategy decreases in the first few years, and only after that a substantial increment is added to the total profit of the whole project. But both the works [5, 7] did not take into account the wind instability and statistical peculiarities. Wind statistics remind a narrow-band filter that cuts off a lot of potential power [6, 7]. Especially, when the wind speed (WS) is about 1.5 to 3.5 m/s. The question is what if we use a series of different WTs whose power curves (PCs) are shifted against each other? This might distribute PCs for light, moderate, and strong winds so that breezes, which are closer to the average WS (AWS) and below the rated-out WS (of a PC), could be used more effectively (see a sketch of this idea in Fig. 1).

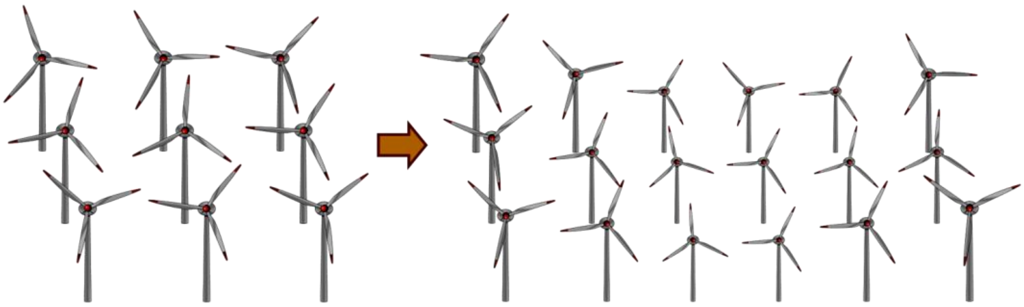

Fig. 1. An idea of converting a WF of individual WTs into a WF of different WTs

Goal of the article and tasks to be accomplished

Under suggestion of that a series of WTs with different PCs might produce greater power expectation than that of identical WTs, the goal is to determine conditions for the series. A constraint is an amount of nominal power (NP) of those WTs should be equal to a given identical WTs' power. To reach the goal, there are the following tasks:

1. To formulate a problem of maximizing the power from WTs with different PCs.
2. To check a hypothesis on possibility of increasing WPE for a WF of real WTs.

Maximization task and check of a hypothesis on possibility of increasing WPE

Let $w(k, s)$ be a PC of a k-th WT, where s is WS in meters per second, and $w(k, s)$ is in megawatts (MW). Suppose that a series of K WTs exists, so $k = \overline{1, K}$. NP of the k-th WT is

$$\bar{w}(k) = \max_{s \in [0; \infty)} w(k, s)$$

and it is held for a range of WS [6, 8]. First, a one WT is selected as that, which would be used for building a WF. Let it be the k_0-th WT, $k_0 \in \{\overline{1, K}\}$. This WT is supposed to have good characteristics of its PC by high NP. The WF is of N such WTs. The expected power output (EPO) of this WF is

$$r(k_0) = N \cdot \int_0^{\infty} p(s) w(k_0, s) ds \tag{1}$$

by the wind statistics given as the Weibull probability density function (PDF) [6]

$$p(s) = (b/a) \cdot (s/a)^{b-1} \cdot e^{-(s/a)^b} \tag{2}$$

with the shape parameter b and the scale parameter a (see in Fig. 2 an example of such a PDF superimposed on PCs). For further consideration, the WF whose EPO is (1) is called a mono-WF (Fig. 1, at the left). Let take a subset of L WTs with indices $I = \{k_l\}_{l=1}^{L} \subset \{\overline{1, K}\}$. Suppose we are building a WF including L those WTs, where the k_l-th WT is installed in $n(k_l)$ places, $n(k_l) \in \mathbb{N}$. EPO of such WF (multi-WF) is

$$r\left(L, I, \{n(k_l)\}_{l=1}^{L}\right) = \sum_{l=1}^{L} n(k_l) \int_0^{\infty} p(s) w(k_l, s) ds . \tag{3}$$

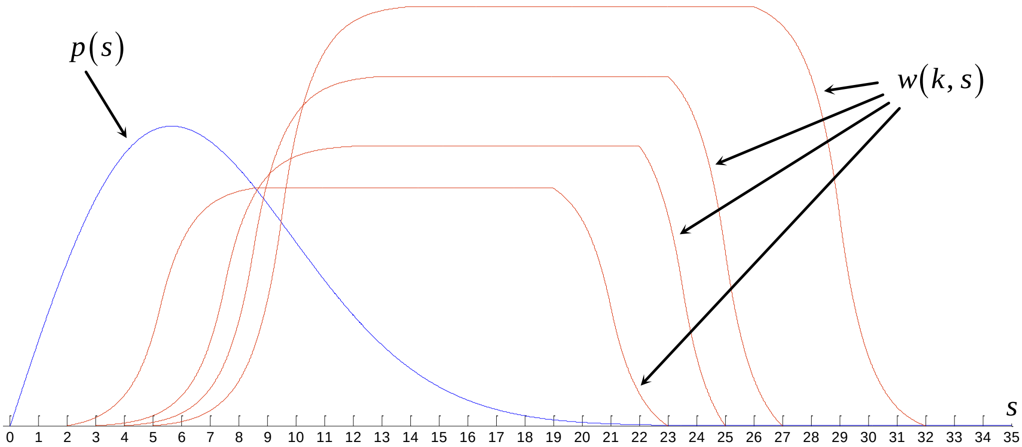

Fig. 2. An example of wind statistics superimposed on PCs (some potential power is cut off)

If those NPs and numbers of places for installing WTs are such that

$$N \cdot \overline{w}(k_0) = \sum_{l=1}^{L} n(k_l) \overline{w}(k_l) \quad \text{by} \quad k_0 \in I , \tag{4}$$

then we might maximize EPO (3) under condition (4) for new combinations of indices I and natural numbers $\{n(k_l)\}_{l=1}^{L}$ along with varying natural numbers N and L:

$$r_* = r\left(L_*, I_*, \{n_*(k_l)\}_{l=1}^{L_*}\right) = \max_{N \in \mathbb{N} \setminus \{1\},\, L = \overline{2, K},\, \{k_l\}_{l=1}^{L} \subset \{\overline{1, K}\},\, n(k_l) \in \mathbb{N}} \left\{ r\left(L, I, \{n(k_l)\}_{l=1}^{L}\right) \right\} . \tag{5}$$

The hypothesis is whether inequality

$$r(k_0) < r\left(L_*, I_*, \{n_*(k_l)\}_{l=1}^{L_*}\right) \text{ by } M_* = \sum_{l=1}^{L_*} n_*(k_l) \tag{6}$$

is possible at practice, wherein costs of mono-WF and of multi-WF are presumed to be approximately the same due to (4). This hypothesis can be checked via solving the problem (5) with integer selection routine (ISR). By ISR, some limit $\hat{N}$ for N is given (which may be considered as an ultimate total cost could be paid for installing a WF), and some L is assigned. Indices in the set I are fixed as well. Then, starting off $N = 2$, we select only those numbers $\{n(k_l)\}_{l=1}^{L}$ that satisfy (4). Thus, EPOs (3) and (1) are calculated and compared until $N > \hat{N}$. The selected numbers $\{n(k_l)\}_{l=1}^{L}$ giving the greatest EPO (3) are stored for those number L and set I. Deeper, L and I are changed as well. In the end, some L_*, I_*, $\{n_*(k_l)\}_{l=1}^{L_*}$, giving the greatest EPO (3) are caught. Surely, if L and I are known beforehand, the search by ISR becomes simpler.

The hypothesis on possibility of increasing WPE is going to be checked over five known and widespread WTs: Enercon E82 E2 (2.3 MW), Gamesa G128-4.5 MW, Nordex N90/2500 (2.5 MW), REpower MM82 (2 MW), Vestas V112-3.0 MW (their characteristics are downloadable from [8]). For further, enumerate them from #1 to #5, respectively. Obviously, the Gamesa WT is the most powerful, but it is the most expensive. Besides, locating big WTs is another problem (see in Fig. 3, for instance, how Enercon WTs are located). Thus, consider the rest four WTs, among which we take Vestas WT as that single k_0-th WT: $k_0 = 5$, $L = 4$, $I = \{1, 3, 4, 5\}$. PCs of these WTs are plotted after real measurements [8]. Wind statistics may be taken optionally, without tethering to a region. In Northern Europe and most other locations around the world the shape parameter value is approximately $b = 2$, so PDF (2) becomes a Rayleigh distribution PDF. The scale parameter is determined by an AWS [6, 7].

Fig. 3. Location of Enercon WTs having a storm control feature that smoothes PCs at the right

For $a = 7$ corresponding to AWS 6.2 m/s, a mono-WF of 10 Vestas WTs gives EPO $r(5) = 6.6658$ MW, whereas taking just single Vestas WT, 5 Enercon WTs, 3 Nordex WTs, and 4 REpower WTs gives 7.6276 MW. Here, this is EPO that solves the task (5) and confirms inequality (6), wherein

$$n_*(1) = 5,\ n_*(3) = 3,\ n_*(4) = 4,\ n_*(5) = 1.$$

The gain of such multi-WF is obvious: $r_*/r(k_0) = 1.1443$, that is more than 14 %. If $\hat{N} = 20$ then a mono-WF of 19 Vestas WTs loses versus a multi-WF by

$$n_*(1) = 5,\ n_*(3) = 1,\ n_*(4) = 20,\ n_*(5) = 1,$$

giving 14.6888 MW, for almost 16 %. When AWS is lower (4 m/s for $a = 4.51$), the gain increases (Fig. 4): it is 27 % by the same mono-WF and numbers n_*'s, although the multi-WF's EPO now is 4.5554 MW (Fig. 5). For AWS closer to cut-in speeds of many WTs, this tendency is kept: the gain increases while the multi-WF's EPO drops. For $a = 3.95$ AWS is 3.5 m/s, and the gain is 30.1 % versus 2.9562 MW of the multi-WF's EPO by the same integers. If $\hat{N}$ is increased, the gain slowly increases, though multi-WF's EPO increases faster. An inconvenient gap in the multi-WF is that numbers $\left\{n_*(k_l)\right\}_{l=1}^{L_*} \setminus \{k_0\}$ are likely to be far from a quasi-uniform distribution (e. g., some types of WTs are installed just once). This may cause extra costs for installing and maintaining multi-WF. But imposing new constraints on task (5) is not desirable because it badly narrows the solution. Once task (5) is solved, we can only try to decrease L_* and "smooth" numbers n_*'s.

Fig. 4. The gain of using multi-WFs

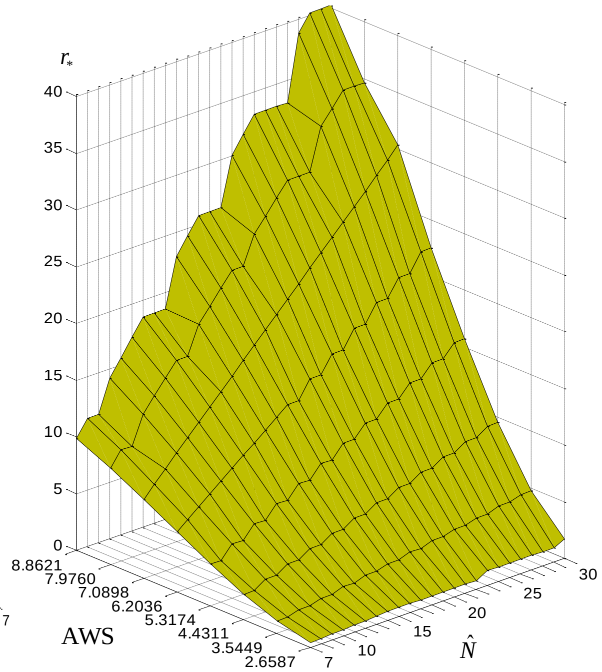

Fig. 5. The best EPO (in MW) of multi-WFs

Certainly, a condition exists when (6) is impossible and task (5) is useless. Thus, if

$$\exists I_K = \left\{k_l^{**}\right\}_{l=1}^{K} = \left\{\overline{1,\, K}\right\} \text{ such that } w\left(k_l^{**}, s\right) > w\left(k_{l+1}^{**}, s\right) \;\; \forall\, l = \overline{1,\, K-1} \qquad (7)$$

then that all does not make a sense, because the k_1^{**}-th WT can be taken, and then $r\left(k_1^{**}\right) > r\left(I\right)$ for any subset I. Hence, the maximization task (5) may make a sense when inequalities (7) are impossible for any indices' order I_K. The best case is when the bunch of those PCs $\left\{w\left(k, s\right)\right\}_{k=1}^{K}$ is a Pareto-like functional set (PLFS), i. e. inequality $w\left(k, s\right) > w\left(j, s\right)$ is false for any indices $k = \overline{1,\, K}$ and $j = \overline{1,\, K}$ by $k \neq j$.

Conclusion and an outlook for further research of increasing WPE

A prime condition for a series of different WTs that, as a multi-WF, might produce a greater EPO than a mono-WF by (4), is determined as a requirement of that there should not be dominating PCs making (7). Another condition is the bunch of those PCs within the multi-WF should remind a PLFS. Constraint (4) is inserted by default, although that equality does not necessarily imply equality of mono- and multi-WF costs. An approximate cost equality (ACE) is believed to be when number M_* is not too much greater than N, as installation of a WT is expensive itself regardless its NP.

The greater gain is for smaller areas. According to the last three examples, although we need to buy and install 27 WTs for the multi-WF, their cost is comparable to the higher-NP 19 WTs of the mono-WF. In a further research, there could be an additional constraint to task (5) — to fulfill an ACE between the mono- and multi-WF costs, along with (4). Then, however, constraint (4) can be relaxed in order to get closer to a cost equality. In that way, we will have the cost equality opposed to NPs' equality.

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