Consideration of Wind Farm Wake Effect in Power System Dynamic Simulation

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Abstract-- **This paper deals with the modelling of the wake effect in wind farms for use in dynamic power system simulation software. First, basic relationships describing the leeside wind speed as a function of the incoming wind speed under ideal conditions are put together. Through aerodynamic efficiency considerations the ideal power-coefficient of the turbine is then related to the actual power coefficient provided by the turbine manufacturer. Finally, mathematical expressions are formulated for the wake wind speed in relation to location within the park and the wind direction. The model thus obtained is implemented on a power system simulation package as an additional feature. Together with the full range of capabilities of the package for steady state as well as dynamic analysis, the model enables an in-depth study of the wake effect and its impact on the farm in terms of output power and its interactions with the network. Some results illustrating the impact of the wake effect on steady state system operation have been presented.**

Index Terms-- **Wake effect, Wind farm, Power system**

I. INTRODUCTION

WIND generators generate electricity by tapping into the energy in the wind. Consequently, the air mass leaving the turbine must have lower energy content and by implication lower speed than the air arriving in front of the turbine. In other words, the turbine positioned upstream in the wind direction influences the wind speed at turbine locations on its downwind (lee) side. This shadowing effect from upstream turbines on other turbines further downstream is referred to as the wake effect.

The implication of the wake effect is that the speed of free wind can be used for computation of mechanical power only for those turbines facing the wind up front. For all other turbines the applicable speed needs to be determined, possibly by taking the cumulative effect of multiple upstream turbines into consideration

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The exact modeling of the wind speed distribution within a wind park is a fairly complicated task. It presupposes the numerical solution of a system of partial differential equations describing the physical process. On top of this, many of the parameters needed are not routinely available with any degree of certainty. It is unlikely that the computational effort alone, not backed up by reliable parameters, can yield satisfactory results.

In this paper a simplified approach for the simulation of the wake effect is presented, which uses only the commonly available parameters and data of the wind park and the turbines within the park. Except for the simplification of the complex physical processes, other aspects of the wake effect, such as the cumulative impact of multiple shadowing, the effect of wind direction, are all taken into consideration. Additionally the use of simplified algorithms enables the modeling of large wind parks with any number of turbines with ease.

II. REVIEW OF BASIC RELATIONSHIPS

Wind generators convert the kinetic energy of wind into electrical energy. The power associated with a mass of air (m) approaching at the speed (v_0) a wind turbine spanning a cross-sectional area (A) is given by the expression:

$$P_0 = \frac{1}{2} \cdot \frac{\partial m}{\partial t} \cdot v_0^2 \quad (1)$$

Only a fraction of the total kinetic energy of the air streaming through the turbine blades can be extracted and converted to rotational power at the shaft. Assuming the wind speed far upstream and far downstream of the turbine to be v_0 and v_{w0}, respectively, the theoretical maximum extractable power by the turbine can be given as:

$$P_{mech\_th} = \frac{1}{2} \cdot \frac{\partial m}{\partial t} \cdot \left(v_0^2 - v_{w0}^2\right) \quad (2)$$

It follows from (2) that if $v_{w0} = v_0$ the power extracted is zero. Similarly, $v_{w0} = 0$ would result in zero power at the turbine shaft since it would imply a complete hold-up of air and thus a mass flow rate of zero. According to the Rankine – Froude theorem [6], the wind speed at the rotor plane is:

$$v_{turb} = \frac{v_0 + v_{w0}}{2} \quad (3)$$

It then follows for the mass flow rate:

$$\frac{\partial m}{\partial t} = \rho \cdot A \cdot v_{turb} \quad (4)$$

where ρ is the density of air. Substituting (4) into (2) and re-arranging, we obtain for the mechanical power:

$$P_{mech\_th} = P_0 \cdot c_{p\_th} \qquad (5)$$

The factor c_{p_th} relating the maximum extractable power P_{mech_th} to the total power contained in the wind (P_0) is given by the relationship:

$$c_{p\_th} = \frac{1}{2}\left(1 + \frac{v_{w0}}{v_0}\right)\left(1 - \frac{v_{w0}^2}{v_0^2}\right) \qquad (6)$$

It goes without saying that the actual power at the shaft of the turbine (P_{mech}) is smaller than the one given by (5) due to the unavoidable losses, which depend, among other things, on the tip speed ratio (λ) and the pitch angle (β). Accordingly, the power coefficient corresponding to the mechanical power at the turbine shaft (P_{mech}) can be given as:

$$c_p = c_{p\_th} \cdot \eta \qquad (7)$$

where η accounts for the power reduction as a result of the combined losses and c_p is the power coefficient of the turbine. Finally, we have for the mechanical power extractable from the wind:

$$P_{mech} = c_p \cdot P_0 \qquad (8)$$

III. TURBINE LEESIDE WIND SPEED AND AERODYNAMIC EFFICIENCY

It is known that the wind directly past a turbine in the downwind direction is characterised by intense turbulence. According to [1], a distance of at least five times the rotor diameter is generally recommended for any two back-to-back turbines to reduce the stress on the turbines arising from the turbulence. But more relevant to the issue at hand is the fact that the leeside wind velocity does not lend itself to simple analytical expression in relation to the incoming wind velocity. As a first approximation, for known c_{p_th} the wind speed behind the turbine (outside the immediate turbulence zone) can be calculated using the relationship given in equation (6).

IV. Leeside speed in relation to the free wind speed

The task now is to determine c_{p_th} using appropriate turbine data so that v_{rot} in relation to the incoming wind speed (v_0) can be determined on the basis of the relationship given in (6).

First, an explicit expression for $v_{w0} = f(c_{p\_th})$ will be derived. For this purpose, the bounds of the values of c_{p_th} need to be determined. The maximum value is obtained by differentiating equation (6) with respect to v_{w0}/v_0 and setting the result zero, which leads to $v_{w0}/v_0 = 1/3$. The corresponding maximum value for the ideal power coefficient is the well known Betz limit, $c_{p\text{-}Betz}$=16/27≅59.3%, which entails that it is physically impossible to extract more than 59.3% of the power in the wind. Consequently, with the minimum possible value for the power coefficient being zero, it can be concluded that all practical values of c_{p_th} lie within the range: $0 \le c_{p\_th} \le c_{p\_Betz}$

With the range of values for the ideal power coefficient identified, an algebraic manipulation yields the following set of solutions for (6):

$$\frac{v_{w0}}{v_0} = \frac{4 \cdot \cos(\varphi/3) - 1}{3} \quad \text{for } c_{p\_th} < \frac{8}{27} \qquad (9)$$

$$\frac{v_{w0}}{v_0} = -\frac{4 \cdot \cos((2\pi + \theta)/3) + 1}{3} \quad \text{for } c_{p\_th} \ge \frac{8}{27} \qquad (10)$$

with

$$\varphi = \cos^{-1}\left(1 - \frac{27}{8} \cdot c_{p\_th}\right) \text{ and } \theta = 180 - \varphi \qquad (11)$$

Now that the relationship between the wind speed behind the turbine (in relation to the speed in front of the turbine) and the ideal power coefficient established, the next task is to introduce the power coefficient into the relationship by incorporating the loss relationships.

V. Determination of the losses via aerodynamic efficiency considerations

Loss in this context is to be understood as the difference between the theoretically available power emanating from wind speed change and the actual mechanical power at the turbine shaft. The major losses to be considered are the profile loss, swirl loss and the loss due to wake rotation.

Profile loss is caused by the drag of the profile, and is directly proportional to the tip speed ratio (λ) and inversely proportional to the lift-drag ratio (ε) of the profile. Assuming a single profile type over the entire blade length and a fixed pitch angle, the output power reduction as a result of the profile loss would be:

$$\eta_{profil} = 1 - \frac{\lambda}{\varepsilon} \qquad (12)$$

The swirl loss is caused by the vortex that is formed in the area around the tip of the turbine as the freely streaming air mass in the vicinity of the turbine and the air flowing over the blade form a confluence. In allusion to its location, this loss is also termed as the tip loss. The swirl loss is inversely proportional to the product of tip speed ratio and the number of turbine blades (n), and can be approximated by the following relationship:

$$\eta_{wirbel} = 1 - \frac{1.84}{n \cdot \lambda} \qquad (13)$$

The loss due to wake rotation takes into account the fact that the air passing through the turbine is not only retarded from its upstream speed but it also experiences a change of direction when it streams past the turbine as an inevitable result of Newton's third law ('for every action there is an equal and opposite reaction'). Accounting for this downstream tangential angular momentum in the determination of the wake wind speed is a relatively difficult task. In [3], it is stated that the optimum power coefficient with all other losses, except the loss due to wake rotation, neglected can be determined using the following relationship with reasonable accuracy:

$$c_{p\_opt} = \frac{16}{27}\cdot\left(1 - \frac{0.219}{\lambda^2} - \frac{0.106}{\lambda^4} - \frac{2}{9}\cdot\frac{\ln\lambda^2}{\lambda^2}\right) \quad (14)$$

The approximate relationships for the losses, which have been put together, will now be used to find an expression for c_{p_th} in relation to c_p.

Normally, a turbine achieves its maximum aerodynamic efficiency at its design tip speed ratio (λ_D). Thus,

$$c_{p\_max} = c_{p\_opt}\cdot\eta \quad (15)$$

where η represents the power reduction as a result of the profile and tip losses.

As can be seen in equations (12) and (13), one of the loss components increases while the other decreases with the tip speed ratio. The product (η) determined at the design tip speed ratio of the turbine, therefore, is assumed to vary only marginally over the normal range of turbine operation. As a result,

$$\eta = \frac{c_{p\_max}}{c_{p\_opt}} \quad (16)$$

It therefore follows from (14) together with (7) for the theoretical power coefficient:

$$c_{p\_th} = c_p\frac{c_{p\_opt}}{c_{p\_max}} \quad (17)$$

In summary, for the determination of $c_{p\text{-}th}$ (and then in a subsequent step v_{w0}/v_0) as a function of the tip speed ratio in effect only the power coefficient (c_p) curve is needed, since c_{pmax} can also be obtained from the same curve.

For the validation of the results obtained using this approach, leeside wind speed as a function of the incoming wind speed was computed for a specific profile type with a power rating in the MW range and compared with the result obtained using the wake model used in [3, 4]. The latter model uses the thrust coefficient (c_t) rather than the power coefficient used in this paper. The discrepancy between the two results, as can be seen in Figure 1, is minimal except for the practically unimportant range near and below the cut-in speed.

VI. Determination of Wake Wind Speed

Up to this point, we have described the theoretical framework for the computation of leeside wind speed for any turbine as a function of its design values and the incoming wind speed. As the wind streams along to other turbine locations, it undergoes further speed change. Accordingly, a functional relationship between the wind speed and the location within the park needs to be established.

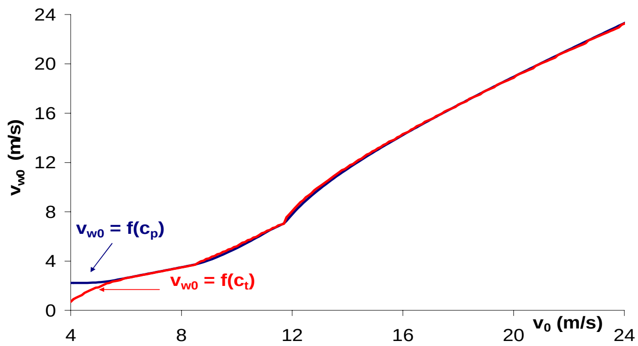

Figure 1: Leeside wind speeds computed using c_p and c_t

The path taken by the wind traversing in the downwind direction past the turbine is represented by a cone. The radius of the (shadow) cone as a function of the radial distance from the turbine location can be calculated using:

$$r(x) = r_{rot} + \tan\alpha\cdot x \quad (18)$$

where r(x) = radius of the shadow cone, r_{rot} = radius of the shadowing (upstream) turbine, x = the radial distance between the turbine and an arbitrary location, α = the apex factor of the cone. The factor $\tan\alpha$ assumes two possible values depending on the nature of the incoming wind. For a free wind, i.e. not affected by any upstream turbine, $\tan\alpha$ = 0.04, otherwise a value of 0.08 should be used for $\tan\alpha$ [4], [5].

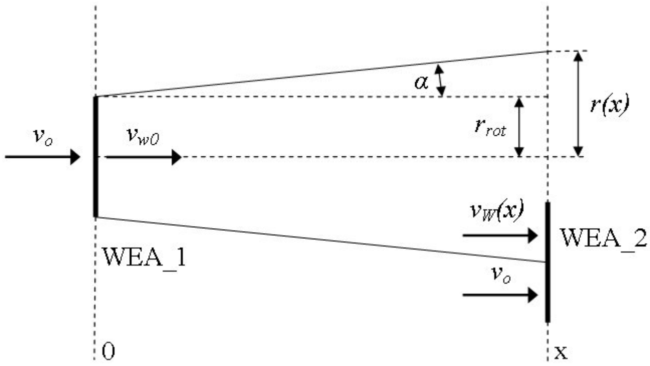

Figure 2: turbine and shadow cone

The level of overlapping of the area spanned by the shadow cone ($A_{(x)}$) with the area swept by the rotor of the turbine experiencing shadowing (A_{rot}) is the measure of the shadowing. There are four distinct shadowing possibilities, namely, complete shadowing, quasi complete shadowing, partial shadowing and no shadowing. A turbine is said to be fully under shadow if A_{rot} lies completely within $A_{(x)}$, otherwise the shadowing is partial or none at all. Quasi complete shadowing is a version of complete shadowing with the rare special case where the cone cross-sectional area of an upstream turbine is less than the area spanned by the shadowed turbine, implying that a small turbine is shadowing a much bigger downstream turbine. Figure 3 elucidates the situation for a partial shadowing.

For the area of the turbine under shadow (A_{shad} = the area A_1 + A_2 in Figure 3), it follows from basic trigonometric relationships:

$$A_{shad} = r(x)^2 \cdot \cos^{-1}\left(d_1 / r(x)\right) + r_{rot}^2 \cdot \cos^{-1}\left(\left(d - d_1\right)/ r_{rot}\right) - d \cdot z \qquad (19)$$

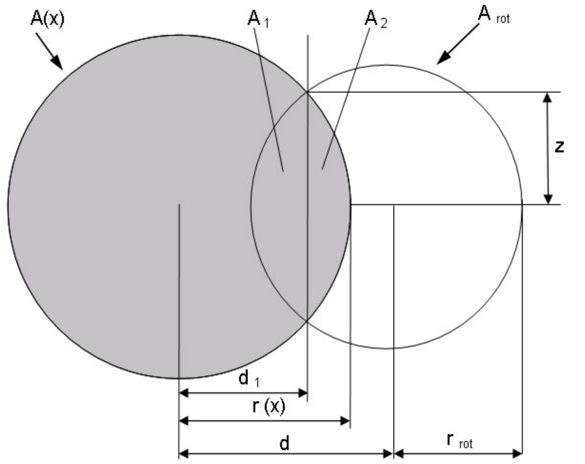

Figure 3: Area swept by the turbine and cast by the shadow cone

Assuming a steady, one-dimensional air flow, the wake wind speed can be computed on the basis of the principle of mass conservation, or more precisely on its corollary, the continuity equation. At the outlet, i.e. at the location for which the wake speed is to be calculated, the mass flow rate is given by:

$$\frac{\partial m}{\partial t} = A(x) \cdot v_w(x) \cdot \rho \qquad (20)$$

The air sweeping through the corresponding cross-section at the upstream turbine location has two different speeds, the free wind speed (v_0) and the leeside speed (v_{w0}) leading to the mass flow rate of:

$$\frac{\partial m}{\partial t} = A_{rot} \cdot v_{w0} \cdot \rho + (A(x) - A_{rot}) \cdot v_0 \cdot \rho \qquad (21)$$

Equating (19) and (20) in accordance with the continuity equation, we have

$$A_{rot} \cdot v_{w0} \cdot \rho + \left(A(x) - A_{rot}\right) \cdot v_0 \cdot \rho = A(x) \cdot v_w(x) \cdot \rho \qquad (22)$$

which leads to a wake speed at the downwind turbine location as a function of the incoming wind speed:

$$v_w(x, t + \frac{x}{v_{w0}}) = v_0(t + \frac{x}{v_{w0}}) + \left(v_{w0}(t) - v_0(t + \frac{x}{v_{w0}})\right) \cdot \left(\frac{r_{rot}}{r(x)}\right)^2 \qquad (23)$$

The reference axis for the location (x) may be chosen arbitrarily. Once the reference is fixed, the term x/v_{w0} in (23) represents the travel time of the wind between the reference and any arbitrary point within the park.

VII. AVERAGE WIND SPEED

As stated above, wind turbines in a wind farm may experience varying degrees of shadowing from upstream turbines ranging from none at all to total eclipse. The next step in the modeling process, therefore, is the determination of resultant wind speeds at each and every turbine location in relation to the speed of the free wind taking all eventualities into consideration.

This can be accomplished by using the law of momentum conservation, which leads to the following relationship [4, 8]:

$$v_j(t) = v_{j0}(t) + \sqrt{\sum_{\substack{k=1 \\ k \neq j}}^{n} \beta_k \cdot \left(v_{w\_k}(x_{kj}, t) - v_{j0}(t)\right)^2} \qquad (24)$$

where v_j = the resultant wind speed for an arbitrary turbine j, $v_{w\text{-}k}(x_{kj})$ = the speed of the wind approaching turbine j (with turbine k as the shadowing turbine), v_{j0} = the incoming wind at the turbine location j without any shadowing. The quotient $\beta_k = \frac{A_{shad\_jk}}{A_{rot\_j}}$ represents the ratio of that part of the area of turbine j under the shadow of turbine k to its total area, n = the total number of turbines.

VIII. IMPLEMENTATION OF THE WAKE MODEL ON POWER SYSTEM SIMULATION PACKAGE

The main objective of this study is to incorporate the algorithms briefly outlined above into a power system dynamic simulation package as an additional feature. The task then is to evaluate the impact of the wake effect on steady-state operation, as well as on the dynamic performance of the system.

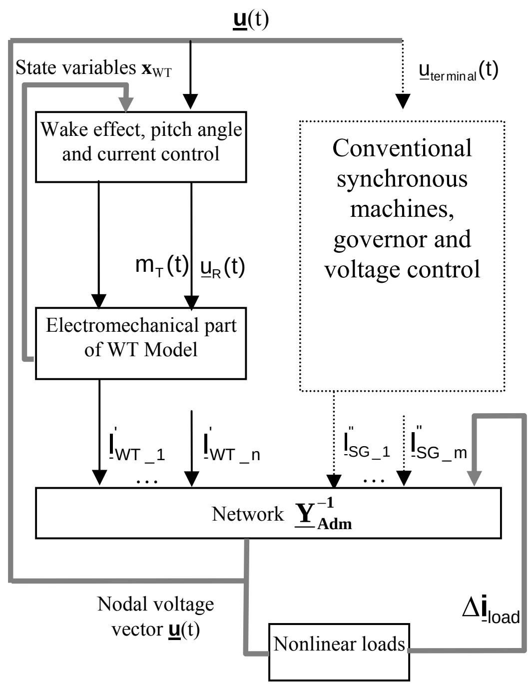

Fig. 4: Overview of the simulation environment

For a quantitative evaluation of the overall impact of the wake effect on the output power of the wind farm, a wake coefficient has been defined as follows:

$$c_{Wake} = \frac{\text{total output power with wake effect}}{\text{total output power neglecting wake effect}} \qquad (25)$$

A. Overall simulation environment

The wake algorithms were then linked up with the simulation package PSD (Power System Dynamics) [9] in the manner shown in Figure 4. The PSD is a simulation tool with a wide range of computational capabilities for all dynamic problems in power systems.

B. Detailed structure of the wake model

That part of the simulation structure, which specifically deals with the wake effect, is further expounded using Figure 5.

The wake model necessitates as input data the site plan of the wind farm together with the coordinates of each turbine location within the farm. On the basis of this information and the impact chain set in motion by a given wind direction, the computational sequence for the wind turbines is determined in an initial single step. Then, the resultant wind speed for each turbine is computed taking all possible influences from the other turbines using (24), which then leads to the mechanical power for each turbine to be calculated in accordance with (2). Using (9) and (10) together with the power coefficient curve, the leeside speed (for use in locations further downstream) is computed. The progression of this speed away from the turbine location is described by (23).

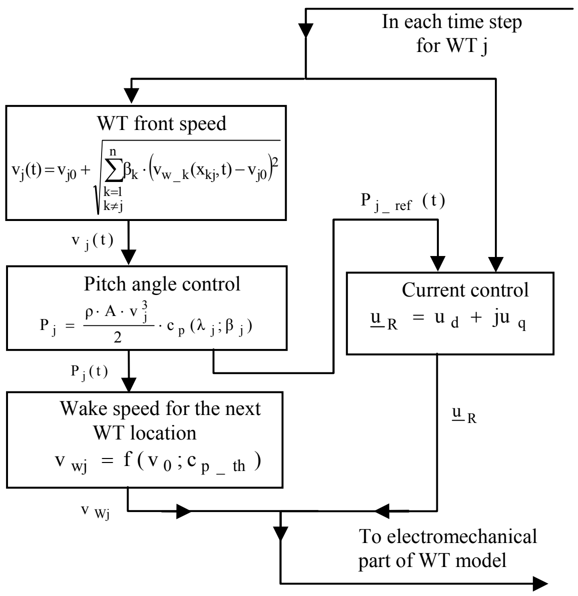

Figure 5: Implementation of the wake model

C. Test network

The network shown in Fig. 6 has been used as the test network. It contains 18 wind units (each consisting of a stall-controlled turbine operating on a squirrel cage induction machine plus a step-up (1kV/33kV) transformer) arranged in a manner shown in the figure.

The wind generators jointly were then connected to the network via a correspondingly larger transformer. In the present example, the network is represented by an infinite bus, but this is not to be perceived as a restriction in the scope of the model since the package used enables the simulation of a network of any complexity with any necessary detail.

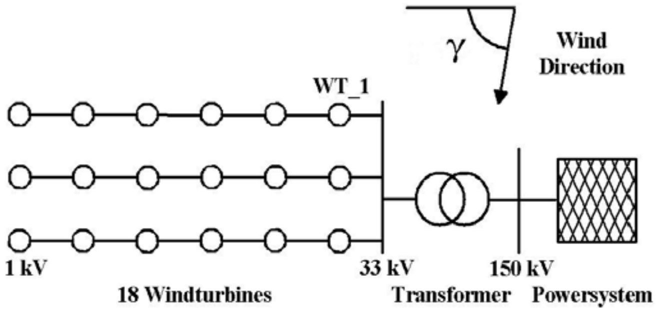

Fig. 6: Test network

IX. Discussion of the Results

Figure 7 depicts the variation of the wake coefficient in relation to wind direction. The figure reflects the steady state phase after the effects of a wind speed change has transpired all-over the wind farm.

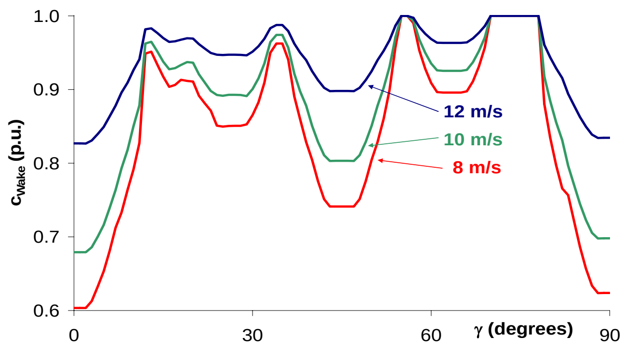

Fig. 7: Wake coefficient in relation to wind direction for different wind speeds

The impact of the wake effect on the output power is strongly related to the wind direction as demonstrated by Fig. 7. For certain wind speed directions, the wake coefficient reaches the maximum possible value of 1.

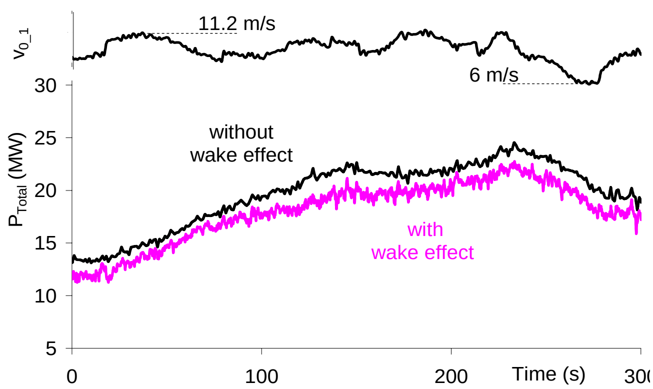

Fig. 8: Output power with and without wake effect

This situation arises when the leeside wind speed - even with the reduction occurring as a result of the wake effect - reaches or exceeds the stall speed of the turbine or in the unlikely event of no shadowing occurring at all.

Figure 8 shows the output power variation during a time interval of some five minutes. The free wind speed as observed at WT_1 (upper plot) varies in a random manner while the direction remains constant at 80°. As expected, the wake effect reduces the output power of the farm, which can be quantified for known wind speed and direction.

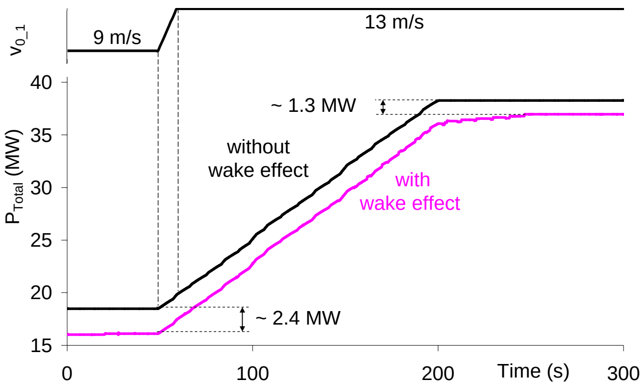

Fig. 9: Output power variation with/without wake effect for wind speed ramp up from 9 m/s to 13 m/s.

Any upstream wind speed change takes effect only after a certain time lag at downstream turbine locations. Accordingly, the process of shadowing bears on downstream turbines in stages and after a time delay. In Fig. 9 mechanical power as a function of time following a wind speed change with and without wake effect are compared. The distinctive feature of the plots is the fact that a relatively fast wind speed change gives rise to a much slower settling time in terms of wind park power variation. On top of this, the wake effect tends to elongate the settling time even further as can be observed in Fig. 9. It can also be observed from the curves that the power reduction as a result of the wake effect drops from 2.4 MW at 9 m/s wind speed to 1.3 MW at 13 m/s wind speed. This is due to the nonlinear relationship that exists between wind speed and power coefficient.

X. PROPSPECTIVE ISSUES OF INTEREST

The detailed simulation of the wake effect and its incorporation into the overall architecture of the wind farm opens up additional possibilities for enhancing the operational efficiency of the wind farm. It will be recalled that the relationship between wind speed and power coefficient is nonlinear. This implies that the pitch-angle control can be centrally coordinated so that the overall output of the farm, instead of the output of individual units, can form the basis for optimization. Consideration of the wake effect enables a more accurate estimation of how a projected wind speed will translate into actual output power. The same applies to the estimation of the rate of increase of output power (power gradient) that can be attained in response to a contingency situation in the power system [7]. Generally the treatment of the wind farm as a single unit experiencing a single wind speed leads to conclusions which may turn out to be too optimistic or too pessimistic depending on the issue under consideration. One such situation is the disconnection of wind turbines as a consequence of wind over speed. Due to the wake effect many downstream turbines experience the full force of the gust only after the upstream turbines are out of operation. As a result, the turbines may in reality be disconnected in stages and not all at once. The consideration of the wake effect enables an insight into the succession of events and provides information with regard to the sequence of loss of generation.

XI. CONCLUSION

As a result of the wake effect, the energy production in a wind farm is reduced by a few percent from what would have been the case with a free air mass throughout the farm. Based on fundamental relationships describing the wind speed variation as a result of obstruction from upstream turbines, this paper outlines how the wind speed at any location within the farm can be determined in relation to the power coefficient of the turbine. The algorithm was then incorporated into a power system simulation package as an additional feature. First results describing the influence of the wake effect on steady state system operation have been presented. The new feature added to the power simulation package enables a comprehensive study of the effect of the wake in a wind farm in interplay with the grid on which it is operating.

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XIII. Biographies

Friedrich W. Koch (1969) is presently a PhD student in the Department of Electrical Power Systems at the University of Duisburg - Essen, Germany. He received his Dipl.-Ing. degree in electrical engineering from the University of Siegen, Germany in 1998. After his studies, he worked in the field of industrial and power plants. He is a member of VDE.

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Fekadu Shewarega (1956) received his Dipl.-Ing. Degree in electrical engineering from the Technical University of Dresden, Germany in 1985. From 1985 to 1988 he pursued his postgraduate studies in the same university and obtained his PhD degree in 1988. After graduation, he joined the Addis Ababa University, Ethiopia as the member of the academic staff where he served in various capacities. Currently he is a member of the research staff at the University Duisburg – Essen. His research interests are focussed on power system analysis and renewable energy technologies.

Istvan Erlich (1953) received his Dipl.-Ing. degree in electrical engineering from the University of Dresden/Germany in 1976. After his studies, he worked in Hungary in the field of electrical distribution networks. From 1979 to 1991, he joined the Department of Electrical Power Systems of the University of Dresden again, where he received his PhD degree in 1983. In the period of 1991 to 1998, he worked with the consulting company EAB in Berlin and the Fraunhofer Institute IITB Dresden respectively. During this time, he also had a teaching assignment at the University of Dresden. Since 1998, he is Professor and head of the Institute of Electrical Power Systems at the University of Duisburg-Essen/Germany. His major scientific interest is focused on power system stability and control, modelling and simulation of power system dynamics including intelligent system applications. He is a member of VDE and IEEE.

Udo Bachmann (1952) received his grad. Engineer degree in electrical power grids and systems from the Leningrad Polytechnic Institute /Russia in 1977. After his studies, he worked in Berlin in the field of development and management by renewal and reconstruction of power grid protection. From 1980 to 1983, he joined the Department of Electrical Power Plant and Systems of the Leningrad Polytechnic Institute again, where he received his Ph.D. degree in 1983. Since 1983 he worked in the National Dispatch Center as Engineer and senior specialist in the field of management of grid protection from system view. During the last 15 years he is responsible both for steady state and dynamic stability computation and short circuit computation as well as network reactions in the Vattenfall Transmission Company (former VEAG Vereinigte Energiewerke AG).