Introduction of Wind Power Generation into the First Course in Power Systems

I. Erlich, *Senior Member, IEEE*, and F. Shewarega, University of Duisburg – Essen

Abstract—This paper argues in favor of a new course dealing with wind energy for power engineering students within the framework of a broader integration of renewable energy technologies into the power engineering curricula. The paper starts by expounding the rationale for such a course and its core contents. The elements of the electromechanical energy conversion process, as they relate to the performance of wind generation plants on an interconnected system, form the basis of the course. The material also includes approaches for assessing wind energy resource and the steps necessary for estimating its economic viability. The course is intended to convey a holistic purview of wind energy from the system perspective.

***Index Terms*—Wind energy, Doubly-fed induction machine, Control system.**

I. INTRODUCTION

THE harnessing of natural phenomena such as sunlight, wind, water flow, ocean waves, etc. for some form of productive use has always been part of the human activity. The widespread and large-scale use of these resources, however, is a fairly recent development. The fossil fuels which still form the backbone of energy production in most industrialised countries draw on finite resources, which are already dwindling and thus becoming more expensive or their retrieval is becoming ever more environmentally damaging. Meanwhile the demand for energy is increasing unabated. It is now generally accepted that meeting the steadily increasing demand for energy solely on the basis of conventional generation technologies puts an unacceptably high stress on the environment. These factors in combination have lent a major impetus to renewable energy based power generation during the preceding two to three decades and the trend is set to continue.

It can be argued that renewable energy technology is not represented in educational programs of higher learning institutions in a manner commensurate with the prominence that it has already attained. One of the causes seems to be the way the educational programs themselves evolve over time. Higher education is typically classified into general education and some major field of specialisation. When it comes to the latter, curriculum designers have often to contend with two seemingly contrasting requirements: the necessity for more specialisation amidst the ever broadening body of knowledge on the one hand and the need for equipping students with skills over a range of interrelated disciplines on the other. Working knowledge on renewable energy is a good example of the latter requirement. Renewable energy technologies are multifaceted in nature. The underlying physical phenomena span a very wide spectrum. In terms of size, they range from a small standalone system for domestic use to a large wind farm on a scale of conventional power plants. The science and engineering basis of renewable energy therefore cuts across the boundaries of many engineering disciplines (including engineering economics) and does not neatly fit into any of the traditional categorisations.

It seems therefore that there is a gap that needs to be filled as regards the representation of renewable energy technology in standard education programs. How best this shortfall can be addressed will be a somewhat evolutionary process. What is already clear however is the fact that a meaningful renewable energy course by its nature must be interdisciplinary and cross-cutting. To indicate how such a course might look like in practice, in this paper a broad outline of a course on wind energy is presented. The course is intended to be offered at undergraduate level as an addendum or independently following the power engineering course. It deviates from the traditional approach for a typical engineering course in the sense that it is broadly conceived and may be offered to students of any of the engineering disciplines and related fields such as engineering economics. The course is intended to impart working knowledge on a range of issues related to the economics and engineering aspects of wind energy without putting too much emphasis on the details. This approach is expected to enable students to understand the essential ingredients that together form the wind energy technology and the interrelationships between them. Presenting the course from the broader perspective in a self-contained way ranging from the resource assessment to the choice of technology together with an initial evaluation of the economic viability of a possible wind power project is more likely to enhance the appreciative perception of students and to foster their methodical competence.

The ‘across-the-board’ nature of the course leaves ample room for the instructor to optionally lay emphasis on particular aspects. For example, for students majoring in electrical engineering the energy conversion aspect,

I.Erlich is with the University of Duisburg-Essen, Duisburg, Germany (e-mail: istvan.erlich@uni-duisburg.de).
F. Shewarega is with the University of Duisburg-Essen, Duisburg, Germany (e-mail: fekadu.shewarega@uni-duisburg.de).

particularly the doubly-fed induction machine and its control systems, may be singled out for an in-depth treatment. An integral part of the proposed curriculum is the extensive utilisation of software and teaching aids to expedite the delivery of the course. RETScreen® and Homer may be cited as examples for calculating the energy production and life-cycle costs and MATLAB for engineering simulation and analysis. RETScreen® is developed by the Canadian Ministry of Natural Resources and Homer by the National Renewable Energy Laboratory and both are provided free of charge for worldwide use. The choice of software of course is bound to change from time to time and the instructor would most likely have his own preferences. It should however be emphasised that given the nature of the material to be covered and the intended objective of the course, one is unlikely to get by without extensive use of software tools and teaching aids.

II. Course Objectives

For most of the 20th century electricity generation had been assumed to face limitless economies of scale, so much so that electricity industry was considered to be a natural monopoly and the industry put forth some of the largest companies. The emergence of new distributed generation technologies together with the favorable framework accorded to renewable energy by many governments has reversed this decades old trend. As a result, the past two decades have seen the role of renewable energy in the international energy portfolio change dramatically. Smaller plant sizes together with market liberalization in turn made the ownership of generation facilities possible for a wider group of people and opened up the field for competition and choice for the consumers.

Obviously graduate profiles change with time as technology, the economic environment or even societal attitudes change. The structural changes that took place in the power sector have also changed the intended capability and key attributes of the graduates of the power engineering programs. Tasks which were carried out centrally by big companies such as formulation of energy management strategies, a variety of supply- and demand-side options, managing generation facilities, etc. are now tasks that need to be carried out at various levels including by small or medium sized companies. A young engineer in the liberalized market environment is expected to see new opportunities for selling energy or securing favorable financing options. To the extent possible, therefore, the objective should be to prepare engineers for the full range of activities. As a result, the courses being offered currently, important as they, need to be augmented by some purpose-built courses.

With the objective of addressing some of the purported gaps, the proposed course touches on all aspects of wind energy. The content, whose details will be introduced in the following section, are categorized in to the following areas:

- Introduction
- Extractable energy in the wind
- Economic assessment of wind resource
- The electromechanical energy conversion process.

III. Course Contents

An undergraduate course normally relies mainly on textbook level knowledge. In this case, however, the technology is in the middle of a rapid change and the textbooks have difficulty catching up with some aspects of the fast-paced development. For this purpose and also to highlight the core knowledge the course should be able to put across, a somewhat detailed, but by no means complete, description of the material to be covered is presented below.

A. Introduction

In line with the usual practice, an introductory chapter precedes the subject matter. Some of the topics to be discussed are:

- Origin of wind including geo-strophic winds, surface winds, mountain winds, sea and land breezes, wind conditions at sea
- Evolution of wind power from non-conventional energy source to the mainstream, which includes history of wind power utilisation, the quantum leap, offshore wind power generation

This section is intended to give background information on assessment of wind resources and to set the stage for a detailed study of the extractable energy in the wind.

B. The extractable energy in the wind

Wind generator converts the kinetic energy of wind into electrical energy. The kinetic energy (E_k) of the mass of air (m) moving at a constant speed (v_w) is given by:

$$E_k = m \cdot v_w^2 / 2 \qquad (1)$$

The power content of this mass of streaming air is the derivative of the kinetic energy with respect to time.

$$P_0 = \partial E_k / \partial t = (\partial m / \partial t) \cdot v_w^2 / 2 = q \cdot v_w^2 / 2 \qquad (2)$$

where the mass flow rate (q) is defined as:

$$q = \rho \cdot A \cdot v_w \qquad (3)$$

ρ and A are the air density and the area traversed by the turbine blades, respectively.

Only a fraction of the total kinetic energy of the air streaming through the turbine blades is available as the rotational power at the shaft on account of several factors, foremost among which is the Betz limit.

1) The Betz Limit

Assuming the wind speed far upstream and far downstream of the turbine are v_0 and v_{w0}, respectively, the theoretical maximum power extracted by the turbine is:

$$P_{mech\_th} = (\partial m / \partial t) \cdot \left(v_0^2 - v_{w0}^2\right) / 2 \qquad (4)$$

It is obvious from (4) that the more energy a wind turbine pulls out of the wind, the more the wind will be slowed down as it leaves the turbine. If we, for example, managed to extract all the energy in the wind, the air would need to move away from the turbine with the speed zero. That would mean that the air could not leave the turbine at all and no energy would have been extracted. In the other extreme case, the wind could pass though the turbine without being hindered at all, i.e. without loosing any speed. No energy would have been extracted from the wind in this case either.

It follows from the foregoing that there must be some optimum way of braking the wind which is in between these two extremes. It turns out that there is in deed an optimum ratio between the wind speed approaching the turbine and leaving the turbine. The power associated with this optimum speed ratio is called the Betz limit.

Betz' law was first formulated by the German physicist Albert Betz in 1919 [1]. The essential statement of the Betz law can be derived in the following simple steps.

Firstly, according to the Rankine – Froude theorem [2], the wind speed at the plane of the rotor (v_{turb}) is:

$$v_{turb} = (v_0 + v_{w0})/2 \tag{5}$$

It then follows for the mass flow rate:

$$q = \partial m / \partial t = \rho \cdot A \cdot v_{turb} \tag{6}$$

Substituting (6) together with (5) in (4), we have

$$\begin{aligned} P_{mech-th} &= \frac{1}{2} \cdot \rho \cdot A \cdot v_{w0}^3 \cdot \frac{1}{2} \cdot \left(1 + (v_{w0}/v_0)\right)\left(1 - \left(v_{w0}^2 / v_0^2\right)\right) \\ &= P_0 \cdot C_{p\_th} \end{aligned} \tag{7}$$

with $P_0 = \rho \cdot A \cdot v_{w0}^3 / 2$ (8)

P_0: the total power content of the wind

$$C_{p\_th} = \left(1 + (v_{w0}/v_0)\right)\left(1 - \left(v_{w0}^2/v_0^2\right)\right)/2 \tag{9}$$

C_{p_th} : the ideal power coefficient.

The term "ideal" is used to characterise C_{p_th} because there are also other unavoidable losses and the actual power coefficient is bound to be significantly smaller in any case. Disregarding the losses for the moment, the maximum possible power can be determined by differentiating C_{p_th} with respect to the speed ratio (v_{w0}/v_0) and setting the derivative to zero, which yields:

$$v_{w0}/v_0 = -1 \ or \ v_{w0}/v_0 = 1/3 \tag{10}$$

As $v_{w0}/v_0 = -1$ does not make sense, the solution obviously is $v_{w0}/v_0=1/3$, resulting in a value for the maximum power coefficient:

$$C_{p\_th} = (1 + (1/3))(1 - (1/9))/2 = 16/27 \approx 59\% \tag{11}$$

Betz' law thus states that one can only convert a maximum 16/27 (or 59%) of the kinetic energy in the wind to mechanical energy using a wind turbine. It is quite remarkable that one can make such a sweeping, general statement which applies to any wind turbine.

Ideally, it is desired that a wind turbine operates at a power coefficient Cp as close to the Betz limit of 0.59 as possible over a wide range of wind speeds. At high wind speeds, Cp might need to be reduced deliberately to limit the power in order to protect the mechanical and electrical components of the machine from overload. As a general rule, a wind turbine operates at maximum Cp until the wind speed reaches the rated power, and then at a progressively lower Cp with increasing wind speed until the maximum allowable wind speed limit is reached. Within the normal range of wind speeds, a more typical aerodynamic efficiency lies between 35% and 45%. A complete wind energy system, including rotor, transmission, generator, storage and other devices, which all contribute towards the overall loss, will deliver somewhere between 10% and 30% of the available energy in the wind.

The mechanical power extracted from the wind can thus be given as:

$$P_{mech} = \rho \cdot \pi \cdot R^2 \cdot C_p(\lambda, \beta) \cdot v_w^3 / 2 \tag{12}$$

P_{mech} : mechanical power, ρ : air density, v_w : wind velocity, R : radius, λ : tip-speed ratio, β : pitch-angle.

The tip-speed ratio is defined as:

$$\lambda = \omega_{tur} \cdot R / v_w \quad (\omega_{tur} \text{ : turbine speed}) \tag{13}$$

2) The power coefficient Cp and the power curve

As stated above and given in (12) in analytical form, Cp relates the wind speed to the available mechanical power at the shaft and combines all the essential aerodynamic properties of a wind turbine. Cp is a turbine specific data and is normally provided by the manufacturer. However, the general pattern of relationships between Cp on the one hand and the pitch-angle β and the tip-speed ratio λ on the other is the same for all turbines and is a subject of further discussion in the following section.

a) Power coefficient

The following generic equation establishes an analytical relationship between Cp and λ with β as a parameter. The equation itself is given in [3] but the notation is slightly modified in line with the one provided in MATLAB [8].

$$C_p(\lambda, \beta) = c1 \cdot (c2/\lambda_i - c3 \cdot \beta - c4) \cdot e^{-\frac{c5}{\lambda_i}} + c6 \cdot \lambda \tag{14}$$

where $\lambda_i = (\lambda + 0.08 \cdot \beta)^{-1} - 0.035 / (\beta^3 + 1)$ (15)

The constants c1 to c6 have the following values: c1=0.5176, c2=116, c3=0.4, c4=5, c5=21, c6=0.068.

The power coefficient characteristics on the basis of (14) for different β values are shown in Fig. 1.

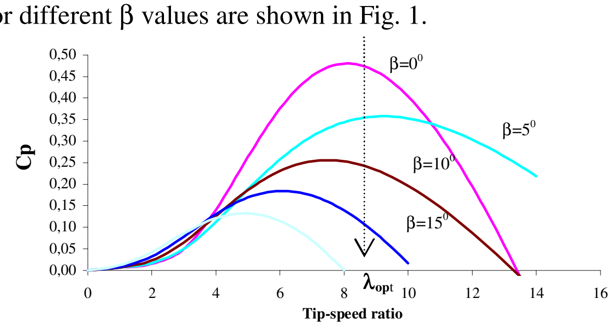

Fig. 1. Power coefficient versus tip speed ratio at different pitch-angle β

The generic relationship (14) exhibits a striking resemblance with the characteristics of many actual turbines and forms a sufficient basis for discussing the underlying relationships. Within the normal range of wind speeds, the pitch-angle is set at β=0. Thus to maximise Cp, λ should be kept at λ_{opt}. In other words, for varying wind speed the turbine speed should be adjusted to result in $\lambda = \lambda_{opt}$ within the practical speed range.

b) The power curve

The power curve relates the output power of a turbine to the wind speed. Determination of the power curve on the basis of the generic formula (14) is a straightforward procedure. Until the wind speed reaches the rated value, the turbine speed is controlled in such a way that Cp = Cp_max, which in this case is about 0.48. A quick glance at (12) reveals that this section of the curve exhibits a cubic relationship with the wind speed. This is followed by an approximately constant power for all wind speeds up to the cut-out wind speed, since the pitch angle in this phase is controlled to reduce Cp and therefore to keep the output power constant despite the wind speed increase. As stated above, in a practical case the power curve of a turbine is provided by the manufacturer.

c) Mechanical power versus turbine speed

The mechanical output power as a function of the turbine speed can also be deduced from (12). For each wind speed value for which power versus turbine speed characteristic is to be determined, express λ as a function of turbine speed using (13). Then read the corresponding Cp values from Fig. 1, which together with the wind speed value are entered into (12) to obtain the corresponding output power. The resulting characteristic curve is given in Fig. 2.

d) The tracking characteristic and the need for speed control

Fig. 2 reveals that for each wind speed there is a specific turbine speed which results in maximum aerodynamic efficiency. Below a certain minimum wind speed, the energy yield is too small to merit the start of the turbine. This speed is called the cut-in speed. As the wind speed increases, the speed of the turbine must also follow suit until the turbine rating is reached. In other words, the turbine must continuously track these maximum power points for each wind speed. The power versus speed characteristic that relates these (maximum power) points to turbine speed is called the tracking characteristic and forms the basis for turbine speed and power control.

C. Economics of wind power generation

The inherent problem associated with wind generation systems is the fact that the primary source of energy, the wind, seldom exhibits a steady, consistent flow. It varies with the time of day, the season, the height above ground, the type of terrain, etc. Since the energy obtained from the wind increases as the cube of the wind speed, a realistic assessment of the local wind speed is a critical element in evaluating the economic viability of any possible wind project.

The software packages RETScreen® and Homer enable a quick assessment of the economic viability of a wind project using only a few inputs. Both packages come with extensive equipment database, electronic textbooks and user manuals, links to wind speed data, etc. It is proposed that the economic analysis be carried out using such hands-on software tools. It takes only a limited set of data to calculate life cycle cost, to assess the green house gas impact of the project or to carry out sensitivity and risk analysis. In this paper, the discussion alludes to the material provided in RETScreen and the electronic textbook [4].

1) Wind speed distribution

The Weibull wind speed distribution is used in wind engineering as it conforms well to the observed long-term distribution of mean wind speeds for a range of sites [4].The Rayleigh wind speed distribution is a special case of the Weibull distribution.

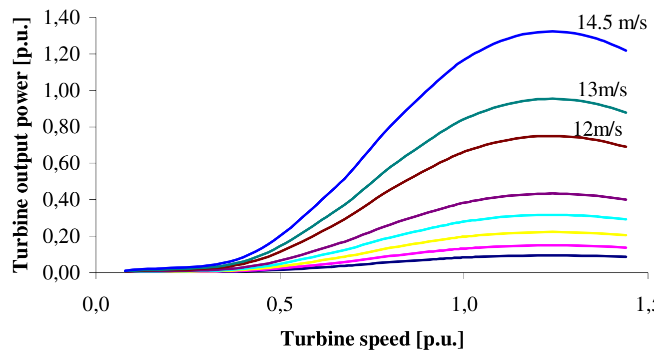

Fig. 2. Output power versus turbine speed (at β=00) at different wind speeds

The Weibull probability density function expresses the probability $p(x)$ to have a wind speed x during the year, as follows:

$$p(x) = (k/C)(x/C)^{k-1}\exp-\left((x/C)^k\right) \quad (16)$$

$$C = x/\Gamma\left(1+\frac{1}{k}\right) \quad (17)$$

where p(x) : the probability of having a wind speed x during the year, k : the shape factor, and Γ represents the gamma-function.

The shape factor (k) is equal to 2 for the Rayleigh distribution. Generally the shape factor lies between 2 and 3.

2) Wind power density

The wind power density WPD, measured in W/m^2, gives the power available for conversion at a particular site.

$$WPD = \sum_{x=0}^{x=25} 0.5\rho x^3 p(x) \quad (18)$$

The actual energy harvested will depend on the size and efficiency of the turbine, and WPD merely gives the density of the available power.

3) Energy production

The energy relationship (19) gives the total amount of energy a wind turbine produces over a range of annual average wind speeds. Beforehand though the wind turbine power curve as a function of wind speed in increments of 1 m/s, from 0 m/s to 25 m/s (Px) need to be specified.

$$E_{\bar{v}} = 8760\sum_{x=0}^{x=25} P_x \cdot p(x) \quad (19)$$

where $E_{\bar{v}}$: point in the energy curve corresponding to mean wind speed $\bar{v}$, Px : the turbine power at wind speed

x, and $p(x)$:the Weibull probability density function for wind speed x.

In (18) and (19), the average wind speed at hub height should be used. If the data available is measurement at anemometer height, the wind shear should be considered. Wind shear is the change in wind speed or direction with height in the atmosphere. In RETScreen for vertical extrapolation of wind speed the following formula is used:

$$v / v_0 = (H / H_0)^{\alpha} \quad (20)$$

where v : the average wind speed at hub height H , v_0 : the wind speed at height H_0 (anemometer height), α : the wind shear exponent.

If a value for α based on experience is not available, the 1/7 power law can be used, i.e. α can be set to 1/7 [5].

4) Estimation of the economic viability of a wind project

To make a preliminary estimation of the economic viability of a possible wind project, cost items such as equipment cost, cost of balance of plant, engineering and development costs, etc. have to be provided. The expected energy yield during the year is calculated using (19). The outputs of the program (in this case RETSCreen) are financial feasibility parameters such as return on investment, pay back time, net present value or internal rate of return. If the project turns out to be not feasible, alternative scenarios that could make the project feasible, such as at what price of fuel or for what amount of renewable energy credit or favourable terms (such as tax holiday, concessional credit, etc.) can be analysed.

D. Choice of wind power generator

Nearly all turbines currently in use employ one of the following machines as generators:

- The squirrel-cage induction generator
- The synchronous generator
- The doubly-fed induction machine

In the subsequent sections, after a brief review of the former two, emphasis will be laid on the doubly-fed induction machine.

1) The squirrel-cage induction machine

The older wind farms commonly use the conventional squirrel-cage induction machine (Fig. 3). The no-load speed of the machine is determined by the grid frequency together with the design parameters (the number of poles and gear transmission ratio). The speed is so chosen that the wind energy at the expected local wind speed can be optimally exploited. During normal operation of the machine, the speed varies within a narrow band in the super-synchronous range, typically between 1% and 2% over the no load speed. The associated turbine is, therefore, usually referred to as constant or fixed speed turbine. In terms of initial investment, it is the least cost option. The squirrel-cage induction machine is well known for its robustness and simplicity in construction. But it is also known for its relative inflexibility with regard to speed versus torque characteristic, which is a huge drawback for application as a wind generator.

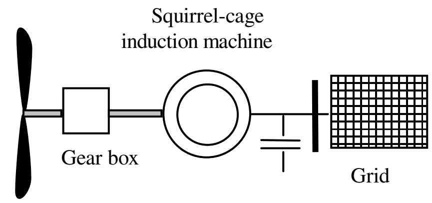

Fig.3. A squirrel-cage induction machine based wind generation system

Constant speed leads to the situation whereby wind speed variations, which occur as a matter of course, directly translate into drive train torque fluctuation and cause higher structural loads, in addition to the fact that it does not enable the optimum tapping of the energy in the wind.

2) The synchronous machine

Fig. 4 shows the connection to the grid of a wind turbine operating on a synchronous machine. The interposing converter decouples the mechanical speed of the machine from the grid frequency. The machine, as a result, can operate at any mechanical speed (within the design limits), leading to the denomination variable speed machine.

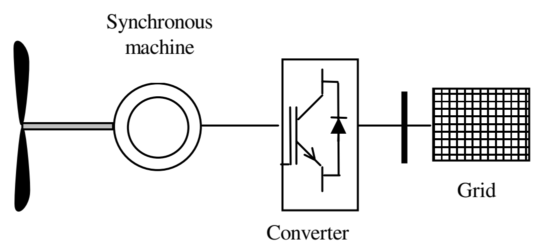

Fig. 4. A synchronous machine based wind generation system

3) The doubly-fed induction machine (DFIM)

The converter in the doubly-fed induction machine provides a rotor voltage that is adjustable both in magnitude and in phase angle (Fig. 5).

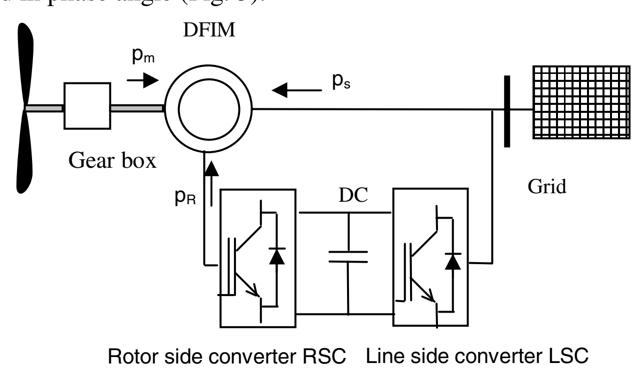

Fig. 5. A DFIM wind generation system

The rotor mechanical speed is then given by the difference between the speeds of the rotating field due to the rotor voltage (which is determined by the rotor voltage frequency) and that of the rotating field due to the stator voltage (which is determined by the grid frequency). The rotor speed can thus be varied to match the optimum operating point in the power-speed curve (tracking characteristic). The possible speed values stretch from the sub-synchronous to super-synchronous ranges.

4) Comparison between the synchronous machine and the DFIM

The synchronous machine and the DFIM in their application for wind power generation are collectively referred to as variable speed machines. They experience less mechanical stress arising from wind speed variation since the rotor absorbs the drive train torque variations by acting as a flywheel and thus storing energy temporarily. As a result, they have the competitive edge over the fixed speed machine in terms of all performance indices. When it comes to the comparison between the two variable speed machines with one another, the choice is not clear cut.

It is obvious from Fig. 4 that the converter of the synchronous machine is designed for the full machine rating, whereas the converter associated with the DFIM handles only the power needed to control the rotor speed (Fig. 5). The maximum rating of the converter can be deduced from the following basic relationships.

The power and torque relationships are governed by the following equations:

$$p_m = t_m \cdot \omega_R \quad (21) \qquad p_s = t_{em} \cdot \omega_s \quad (22)$$

$$p_R + p_m + p_s = 0 \rightarrow p_R = -(p_m + p_s) \quad (23)$$

$$J \frac{d\omega_R}{dt} = t_m + t_{em} \quad (24)$$

where p_R : rotor power, p_S : stator power, t_m : the mechanical torque, t_{em} : the electromagnetic counter-torque, ω_R : rotor speed, ω_s : the synchronous speed, J : the inertia constant.

It follows from $t_m = - t_{em}$ and (23), neglecting losses, that:

$$p_R = -(p_m + p_s) = -(t_m \cdot \omega_R + t_{em} \cdot \omega_s) \rightarrow$$

$$p_R = -s \cdot p_s \quad (25) \text{ with } s = (\omega_s - \omega_R) / \omega_s \quad (26)$$

Thus in operation as a generator the machine delivers power to the grid for s < 0 (at super synchronous speed) and draws power from the grid at s > 0 (sub synchronous speed).

Returning to the issue of converter rating, (25) signifies that the rotor power and thus the converter rating is equal to the product p_s (stator power) and the absolute value of s (the slip). Normally, the magnitude of s (and by implication p_R) is much smaller than 1. It is this feature of the DFIM that tilts the comparison in its favour in comparison to the synchronous machine at the moment. Accordingly, the discussion in the following sections will be restricted to the DFIM only.

E. The DFIM and its control system

1) Mathematical model

Equations (27)-(30) (together with (24)) represent the complete set of mathematical relationships that describe the DFIM in steady state [6], [7].

Voltage equations:

$$\underline{u}_S = r_S \cdot \underline{i}_S + j \cdot \omega_s \cdot \underline{\psi}_S \quad (27)$$

$$\underline{u}_R = r_R \cdot \underline{i}_R + j \cdot (\omega_s - \omega_R) \cdot \underline{\psi}_R \quad (28)$$

Flux linkages:

$$\underline{\psi}_S = l_S \cdot \underline{i}_S + l_h \cdot \underline{i}_R \quad (29) \qquad \underline{\psi}_R = l_h \cdot \underline{i}_S + l_R \cdot \underline{i}_R \quad (30)$$

where $l_S = l_h + l_{\sigma S}$, $l_R = l_h + l_{\sigma R}$, r_S/r_R : stator/rotor resistance, l_S/l_R : stator/rotor inductance, Ψ_S/Ψ_S : stator/rotor flux linkages, $l_{\sigma S}/l_{\sigma R}$: stator/rotor leakage inductances.

Eliminating the flux linkages from (27) and (28) using (29) and (30), we obtain:

$$\underline{u}_S = r_S \underline{i}_S + j\omega_s \cdot (l_S \underline{i}_S + l_h \underline{i}_R) = r_S \underline{i}_S + jx_S \underline{i}_S + jx_h \underline{i}_R \quad (31)$$

$$\frac{\underline{u}_R}{s} = \frac{r_R}{s} \underline{i}_R + j\omega_s \cdot (l_h \underline{i}_S + l_R \underline{i}_R) = \frac{r_R}{s} \underline{i}_R + jx_h \underline{i}_S + jx_R \underline{i}_R \quad (32)$$

The mathematical relationships described by (31) and (32) can be illustrated using the equivalent circuit given as Fig. 6.

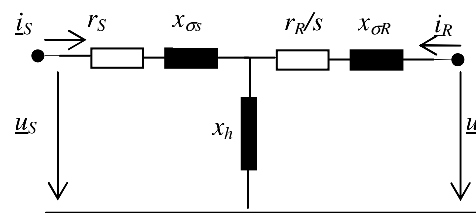

Fig. 6. Equivalent circuit of the DFIM in steady-state

2) Torque, rotor and stator power as a function of the rotor voltage and its angle

The voltage equations (31) and (32) in matrix form:

$$\begin{pmatrix} \underline{u}_S \\ \underline{u}_R / s \end{pmatrix} = \begin{pmatrix} r_S + jx_S & jx_h \\ jx_h & r_R / s + jx_R \end{pmatrix} \cdot \begin{pmatrix} \underline{i}_S \\ \underline{i}_R \end{pmatrix} \quad (33)$$

By inverting (33), we obtain expressions for the current.

$$\begin{pmatrix} \underline{i}_s \\ \underline{i}_R \end{pmatrix} = \begin{pmatrix} \underline{y}_{11} & \underline{y}_{12} \\ \underline{y}_{21} & \underline{y}_{22} \end{pmatrix} \cdot \begin{pmatrix} \underline{u}_s \\ \underline{u}_R / s \end{pmatrix} \quad (34)$$

The total power absorbed/delivered by the machine is:

$$\underline{s} = \underline{u}_S \cdot \underline{i}_s^* + \underline{u}_R \cdot \underline{i}_R^* \quad (35)$$

Substituting (34) in (35), we have:

$$\underline{s} = \underline{i}_S^* \cdot \left(r_S \underline{i}_S + j\omega_0 \underline{\psi}_S\right) + \underline{i}_R^* \cdot \left(r_R \underline{i}_R + j(\omega_s - \omega_R)\underline{\psi}_R\right)$$

After grouping the loss terms together, we obtain:

$$\underline{s} = \underbrace{(r_s + jx_S) \cdot i_S^2 + (r_R + jx_R \cdot s) \cdot i_R^2}_{p_L + jq_L} + \underbrace{jx_h \cdot \left(\underline{i}_S^* \cdot \underline{i}_R + \cdot s \cdot \underline{i}_S \cdot \underline{i}_R^*\right)}_{p_G + jq_G}$$

where $\underline{s}$:the complex power at the terminals of the machine,
$p_L + jq_L$: real and reactive power losses,
$p_G + jq_G$: the internal active and reactive power generation. The real part of the complex power generated by the machine can be given as:

$p_G = \operatorname{Im}\left\{x_h \cdot (1-s) \cdot \underline{i}_S \cdot \underline{i}_R^*\right\}$. Based on this relationship, the power and torque expressions can be defined as follows:

$$p_s = \operatorname{Im}\left\{x_h \cdot \underline{i}_S \cdot \underline{i}_R^*\right\} \quad (36) \qquad p_R = \operatorname{Im}\left\{- s \cdot x_h \cdot \underline{i}_S \cdot \underline{i}_R^*\right\} \quad (37)$$

$$t_{em}= \frac{p_G}{\omega_R} = \mathrm{Im}\left\{l_h \cdot \underline{i}_S \cdot \underline{i}_R^*\right\} \quad (38)$$

where p_S : stator power, p_R : rotor power and t_{em}:electromagnetic torque.

To relate ((36)-(38)) to the magnitude and phase angle of the rotor voltage, first the phase reference is defined as follows:

$$\underline{u}_S = u_S \angle\theta_S \qquad \underline{u}_R = u_R \angle\theta_R \quad and \quad \theta = \theta_S - \theta_R \quad (39)$$

After some re-arrangement, we obtain for the electromagnetic torque:

$$t_{em} = \alpha_T \cdot (u_R / s)^2 + \beta_T \cdot \cos(\theta - \delta_T) \cdot u_R / s + \gamma_T \quad (40)$$

The coefficients (α_T, β_T, δ_T and γ_T) are given in the appendix.

The torque at the synchronous speed (the synchronous torque) can also be obtained by determining the coefficients for s→ 0 in (40), which results in:

$$t_{em-syn} = \alpha_{Syn} \cdot (u_R / s)^2 + \beta_{Syn} \cdot \cos(\theta - \delta_{Syn}) \cdot u_R / s \quad (41)$$

The coefficients α_{syn}, β_{syn}, γ_{syn} are also defined in the appendix. Equation (41) confirms the well known fact that, in the absence of u_R, the machine is not capable of developing torque at the synchronous speed.

Equation (40) (and (41) for the special case that s = 0) establishes an explicit functional relationship between the torque and the rotor voltage. The stator and rotor powers as well as reactive power generations can also be expressed as functions of the rotor voltage in a similar way. It is this property of the machine that makes it amenable to control measures aimed at improving its performance indices during normal operation or contingency situations.

3) Operational range

Self-evidently, the stator winding always delivers power to the grid in operation of the machine as a generator. The direction of the rotor power, however, depends on the speed of the machine. The rotor winding supplies power to the grid at s < 0, while it draws power from the grid via the converter for positive slip values. At synchronous speed the rotor neither draws nor supplies power. The speed of the machine (and with it the speed of the wind turbine) is, therefore, determined by the rotor power p_R.

The rotor power transferred to the converter at super-synchronous speeds tends to raise the voltage of the capacitor in the converter DC link, while at sub-synchronous speeds the reverse situation occurs. It is the task of the grid side converter control to keep the DC voltage constant.

The phase sequence of the AC voltage generated by the rotor side converter constitutes a positive-sequence for the sub-synchronous speed and a negative sequence at super-synchronous speeds. The frequency of the rotor voltage is equal to the product of the grid frequency and the absolute value of the slip. The rotor and the grid side converters can also be used to generate or absorb reactive power or alternatively to control the power factor or the voltage at the grid interconnection point.

4) Control of the DFIM

The DFIM control embodies the following tasks:

- Controlling the pitch-angle to remain constant at zero degree until the turbine reaches the rated speed and then to increase in such a way that the power remains at the rated value despite increasing wind speed.
- Controlling the power to follow a pre-defined power versus speed characteristic
- Controlling the power factor or the voltage magnitude to remain at the prescribed value at the grid interconnection point.

The control tasks listed above are realised through the pitch-angle, the rotor side as well as the grid side converter controls.

The control of the DFIM is a dynamically evolving topic. Apart from manufacturer-specific control concepts, which sometimes are treated as company secrets, there are still open issues with regard to the overall control objective vis-à-vis the contribution of wind generating plants to overall system performance and security. An in-depth discussion of the control structures is beyond the scope of this article. For more detailed treatment of the issue, the reader is referred to [6], [7], [8]. The following paragraphs are merely intended to bring up some core issues that need to be dealt with at some length in the course.

a) Pitch-angle control

When the turbine speed exceeds the nominal speed the pitch controller initiates pitching of the blades so that the mechanical power generated by the wind is reduced.

b) Control of the rotor side converter

The tasks of this controller are two fold: to control the power output and the speed of the machine in such a way that it tallies with the tracking characteristic and also to maintain the voltage magnitude or the power factor within the prescribed range at the point of interconnection with the network. On the basis of the actual turbine speed, the reference for the power control loop is obtained from the tracking characteristic. The output of the power controller is the reference value of the rotor current component that produces the electromagnetic torque t_{em} leading to the optimum turbine speed. In the orthogonal dq coordinate system, this current corresponds to d-axis component assuming that the d-axis is oriented along the direction of the stator voltage phasor in a manner given in (42):

$$\underline{u}_S = u_{Sd} \quad (42)$$

This relationship introduced into the stator power equation yields:

$$\underline{s} = \underline{u}_S \cdot \underline{i}_s^* = (u_{sd} + ju_{sq}) \cdot (i_{sd} - ji_{sq}) = u_S \cdot (i_{sd} - ji_{sq}) \quad (43)$$

Equation (43) reveals that the stator real power p_S and reactive power q_S are proportional to the d-axis and q-axis components of the stator current, respectively.

These current components (i_{Sd} and i_{Sq}) in turn can be related to the corresponding rotor current components. From (31), after neglecting the stator resistance (r_S), we have:

$$\underline{i}_R = -x_S \underline{i}_S / x_h - j\underline{u}_S / x_h \quad (44)$$

which leads to:

$$i_{Rd} = -x_S i_{Sd} / x_h \quad (45) \qquad i_{Rq} = -\left(x_S i_{Sq} + u_S\right) / x_h \quad (46)$$

Thus, reference values for active and reactive stator power outputs directly translate into reference values for the d- and q-axis components of the rotor current. The rotor voltage that leads to the current reference values in accordance with (45) and (46) can also be derived from (31) and (32).

To sum up, the output of the power and voltage/var controller are the reference d- and q-axis rotor currents, respectively. The output of the current controllers is then the corresponding components of the rotor voltage. It should be noted that control of the reactive power through the rotor side converter enables a better utilization of the converter rating and is thus the standard practice, although reactive power control through the grid side converter is also possible.

c) Control of line side converter

The major task of the grid side converter is to control the voltage of the DC link. The output is the active current which is injected into/drawn from the grid node. Concerning reactive current generation the system provides an additional degree of freedom that can be used, for example, for providing enhanced voltage support to the grid during faults. However, the normal practice is to set the reactive current reference to zero and to carry out the reactive power control through the rotor side converter.

IV. Conclusion

This paper provided an overview of a proposed new course on wind energy. The material suggested combines both the economic and engineering aspects of the wind energy. The framework and the software intended for use in the economic analysis easily enable the inclusion of other forms of renewable energy sources to determine the best from the available options or the optimum mix in terms of economic feasibility. The objective of this part of the material is to try to impart a holistic perception including both the pitfalls and the opportunities the renewable energy offers. The course can be considered as an elective or a required course at some stage at senior level.

The major part of the material is devoted to the electromagnetic energy conversion process based on the DFIM. Wind energy has attained a significant role in the energy portfolio over a relatively short period of time to the extent of impacting the overall performance of interconnected systems. On the other hand, how wind generators and their control systems interact with and affect the performance indices of the system is still a fringe issue in power engineering courses. By way of filling this gap, an attempt has been made to put together the core material, which such a course should cover. Given the breadth of the issues involved, the material can be incomplete in view of the space limitation in such a paper. Merely listing the material to be presented in a typical course outline format would very likely have failed to put across the intended message. Embarking on “pick and choose” from the available diverse and wide-ranging material has inevitably been a tightrope walk.

Once the background material is covered, using MATLAB or other established packages as a platform, it should be possible to convey a hands-on exposure and to achieve appreciative perception by students of the salient issues that stand out in wind power generation.

V. Appendix

$$With:\ G_{ik} = \mathrm{Re}\{\underline{y}_{ik}\}\ and\ B_{ik} = \mathrm{Im}\{\underline{y}_{ik}\}:$$

$$\alpha_T = l_h \cdot (G_{22}B_{12} - G_{12}B_{22}); \qquad a = u_s \cdot (G_{22}B_{11} - G_{11}B_{22});$$

$$\beta_T = \sqrt{a^2 + b^2}\ ,\ \delta_T = \tan^{-1}(b/a)$$

$$\gamma_T = u_s{}^2 \cdot \left(G_{21}B_{11} - B_{11}B_{21}\right) \cdot l_h$$

$$\alpha_{Syn} = -r_s \cdot x_h^2 / \omega_0 \cdot r_R^2 \cdot (r_s^2 + x_s^2);$$

$$\beta_{Syn} = u_s \cdot x_h / \omega_0 \cdot r_R \cdot \sqrt{(r_s^2 + x_s^2)}\ ;\ \delta_{Syn} = r_s / x_s$$

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VII. Biographies

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 senior member of IEEE.

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 at the same university in the area of the simulation of power system dynamics 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 focused on power system analysis and renewable energy technologies.