Model of a Wind Turbine with PMSG and Wind Park Configuration

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***Abstract*-Nowadays the number of dispersed generators (DG) is growing rapidly. This change will greatly influence the power system dynamics. A distribution network, where DG are connected to the grid, cannot be considered as passive anymore. So in future it will not be possible to use simple equivalents of distribution networks for power system dynamic modeling as it was before. In dynamic studies the whole power system cannot be represented in a detailed manner because of huge system dimensions. Therefore special techniques have to be applied for aggregation and order-reduction of distribution networks with DG. Future of power generation which is cleaner and more efficient to meet the targets of the Kyoto protocol is a head of us. Distributed energy resources systems are small-scale power generation technologies used to provide an alternative to or an enhancement of the traditional electric power system. Therefore, distributed generation will play a vital part in the future of electricity generation. However the connection of distributed generation may pose several problems to local distribution networks, therefore, analysis and tackling these problem areas will be needed to address new challenges for a network design, operation and modeling of a power system is required of utmost importance. In this paper brief review of load and generation models have been given.**

I. Introduction

As we strive to create a future of power generation which is cleaner and more efficient to meet the targets of the Kyoto protocol and reduce the dependency of our now limited resources of fossil fuel, distributed generation will play a vital part in the future of electricity generation.

Currently, industrial countries generate most of their electricity in large centralized facilities, such as coal, nuclear, hydropower or gas powered plants. These plants have excellent economies of scale, but usually transmit electricity long distance. Most plants are built this way due to a number of economic, health and safety, logistical, environmental, geographical and geological factors.

Distributed generation (DG) is another approach. It reduces the amount of energy lost in transmitting electricity because the electricity is generated very near where it is used, perhaps even in the same place. This also reduces the size and number of power lines that must be constructed. Therefore, distributed energy resources systems are small-scale power generation technologies used to provide an alternative to or an enhancement of the traditional electric power system. It is the expectation that electricity customers will wish to invest in their own local generation system which will make use of these DG technologies [1], [2].

However the connection of distributed generation plants may pose several problems to local distribution networks. Analysis and tackling these problem areas will be needed to address new challenges for network design and operation as well as looking for new methods of modeling of power system network is required of utmost importance. Therefore, power control performance of the DG unit determines its impact on the utility grid it connects to.

The process for analysis have been automated, with the addition of adapted existing load and generation profiles being put in place to provide realistic load and power flows within the network. This analysis will be used to provide an insight to the anticipated behavior of distribution network allowing for the suitability of alternative novel network technologies to be assessed to wider development [2].

II. Description of Generation Models

In recent years, the problem of energy crunch has become more and more aggravating, resulting in increased exploitation and research for new power energy resources around the world. Natural resources in the world have depleted rapidly as mankind venture into the new millennium. The energy consumption is steadily increasing and the deregulation of electricity has caused that the amount of installed production capacity of classical high power stations cannot follow the demand [1]. A method to fill out the gap is to make incentives to invest in alternative energy sources such as photovoltaic systems, biomass and hydropower resources.

III. Model of Wind Turbine with PMSG

As numerous WTG systems have been developed and connected to power systems worldwide, many different wind turbine models have been developed. Three of the most popular wind turbine generator topologies are outlined in Fig. 1 namely, the fixed-speed design employing a squirrel-cage induction-machine and variable-speed designs using the doubly-fed induction generator (DFIG) and the multi-pole synchronous machine.

Each of the wind turbines in Fig. 1 comprises a prime mover and an electrical generator/power system interface. The prime mover consists of the wind-turbine blades, which may include a pitch controller, the wind turbine shaft, and possibly a gearbox. The electrical generators typically comprise squirrel-cage induction machines, wound rotor induction machines, o synchronous machines.

Traditionally, a wind turbine with PMSG is connected to the AC grid through back-to-back full converters. Nowadays, with the evolution of power electronics, voltage source converter based HVDC (VSC-HVDC) has been considered as a feasible solution to integrating wind farms to grids due to its favorable features. The analysis in the paper is under the background of VSC-HVDC.

A. Generator Model

The dynamic model of PMSG is derived from the two-phase synchronous reference frame in which the *q* axis is 90° ahead of the *d*-axis with respect to the direction of rotation. The synchronization between the *dq*-rotating reference frame and the *abc*-three phase frame is maintained by a phase locked loop (PLL).

The electrical model of PMSG in the synchronous reference frame is given in (1),(2).

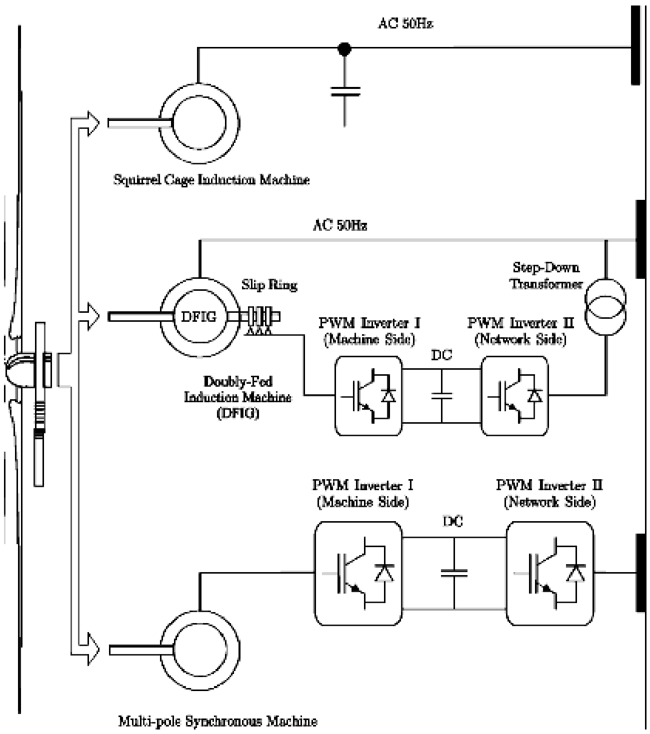

Fig. 1. Fixed-speed, DFIG, and multi-pole synchronous WTG topologies.

$$di_d /dt = (-R_a /L_d)i_d + \omega_e(L_q/L_d)\, i_d + (1/L_d)\, u_d \tag{1}$$

$$di_q/dt = (-R_a /L_q)i_q - \omega_e[(L_q / L_d)i_d + (1/L_q)\, \lambda_0] + (1/L_q\,)u_q \tag{2}$$

where subscripts '*d*' and '*q*' refer to the physical quantities that have been transformed into the *dq*-synchronous rotating reference frame; Ra is the armature resistance; ω_e is the electrical rotating speed which is related to the mechanical rotating speed of the generator as $\omega_e = n_p\omega_g$ where n_p is the number of pole pairs; λ_0 is the permanent magnetic flux. The electric frequency is determined by $f_e = \omega_e/2\pi$. The frequency is obtained by PLL. The inductances, L_d and L_q are the summation of the inductances of the generator on the d- and q-axis and the inductance of the transformer L1, respectively. u_d and u_q are, respectively, the *d*- and *q*-axis components of u_g in Fig.7. The *q*-axis counter electric potential $e_q= \omega_e\lambda_0$ and the d-axis counter electric potential $e_d = 0$. In the paper, we assume $L_d = L_q = L$ and (3), (4) can be rewritten as

$$di_d /dt = (-R_a /L)i_d + \omega_e i_q + (1/L)\, u_d \tag{3}$$

$$di_q /dt = (-R_a /L)id - \omega_e[i_d + (1/L_q)\, \lambda_0] + (1/L)\, u_d \tag{4}$$

For the complete representations of the wind turbine with PMSG the following models are required: Aerodynamic, Pitch Angle Control, Speed Control and Phase Locked Loop. In the [3] all of them have been described clearly.

PMSM model could also be modeled by linearization technique. This proposed method [4],[5], removes the dominant quadratic nonlinearity of the model as well as higher order terms involving the input in the system. PM synchronous motor can be linearized using the following transformations [5],[6]

$$y = x + \phi(x) \tag{5}$$

$$u = (1+ \beta(x))v + a(x) \tag{6}$$

$$x = Ax + Bu + f^2(x) \tag{7}$$

$$x = [x_1\ \ x_2\ \ x_3]^T,\ u=[u_1\ \ u_2]^T \tag{8}$$

$$f^2(x) = [k_1\ \ x_2\ \ x_3;\ k_2\ \ x_3\ \ x_1;\ k_3\ \ x_2\ \ x_1] \tag{9}$$

where k_1, k_2, k_3 are as defined as:

$$k_1 = (L_{ds} - L_{qs})/a_{31}, \tag{10}$$

$$k_2 = (-L_{ds}a_{31})/L_{qs}, \tag{11}$$

$$k_3 = (L_{qs}C_1^{\,2}a_{31})/L_{ds} \tag{12}$$

where a_{31} and C_1 is :

$$a_{31} = (3P^2L_{dm}I_f'/8J),\ C_1 = 1/L_{qs} \tag{13}$$

L_f' is the field current equivalent to the permanent magnet. L_{ds}, L_{qs} and L_{dm} are the direct, quadrature and magnetizing inductances respectively. R_s is the stator resistance. *P* is the number of poles and J is the system moment of inertia. A and B are in Brunovsky form as in:

$$A = [0\ \ 1\ \ 0;\ 0\ \ 0\ \ 1;\ 0\ \ 0\ \ 0] \qquad (14)$$

$$B = [0\ \ 0;\ 0\ \ 1;\ 1\ \ 0] \qquad (15)$$

Equation (7) can be linearised using the transformations (5) and (6) (with (6) modified for the case of two inputs) where

$$\phi(x) = \phi^2(x) = [0;\ k_1\, x_2\, x_3;\ k_1\, x^2_3],\ \alpha(x) = [-k_3 x_2 x_1;\ -k_2 x_3\, x_1] \quad (16)$$

$$\beta^{(m-1)}(x) = (-1)^{m-1}[B^T\{\delta\phi^2(x)/\delta x\}B]^{m-1},\ m \geq 2 \qquad (17)$$

The system then reduces to $y = Ay + Bv$. Proof: See [5],[6].

IV. Wind Farm Model

The mathematical model used for the wind farm behavior in power systems is presented in this section. Typically, the number of wind turbines in a wind farm is high. The example of wind farm is shown in Fig. 2. In fact, a large wind farm can feature hundreds of wind turbines. Therefore, only for wind farm projects it is necessary to analyze in detail the entire generating facility, with each wind turbine represented individually.

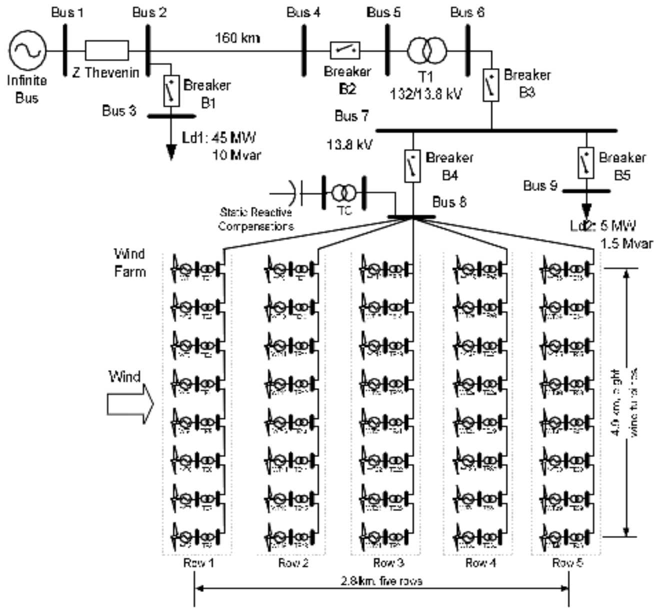

Fig. 2. Example of wind farm model.

In studies where the objective is to verify the influence of the wind farm on the electrical system, the model of every individual turbine of the wind farm would need excessively long processing times and a very robust computational infrastructure. In such studies, the wind farm is represented by an equivalent model from the viewpoint of the electrical system [7].

The simplest way to represent the wind farm is to model the entire farm as an equivalent single wind turbine. This approach assumes that the power fluctuations from each wind turbine are all equal throughout the farm. This assumption, however, does not reflect reality, because the power fluctuations of a wind farm are relatively smaller than those of a wind turbine. Another way to model the wind farm is through a detailed modeling of the farm and considering factors such as the coherence and the correlation of wind turbulence as the presented in. These models imply a heavy load of mathematical modeling and sizable hardware to process them. The model presented in this work takes into account the aggregation effect of the wind farm using an equivalent for the wind added to groups of wind turbines in the farm. The model thus conformed renders a good approximation of the behavior of the wind farm, from the electric system viewpoint. As an advantage, the need for computational resources is reduced [7]

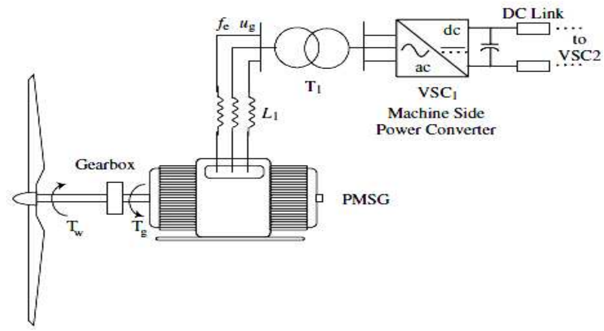

Fig. 3. Dynamic model of an asynchronous generator.

A. *Proposed Linear Dynamic Model Applied to a Wind Park*

In [8] induction generator dynamic model was presented as a Thevenin equivalent voltage source E' behind the impedance $R_s + jX'$ as can be seen in Fig. 3. The proposed linear dynamic model can be applied to a wind park consisting of several asynchronous generators. In this case the variation of stator current, for machine number "*i*," is expressed as:

$$\Delta I_{s,I} = (\Delta U_I - \Delta E'_I)/(R_{s,I} + JX'_I) \qquad (18)$$

where ΔU_i is the nodal voltage defined by nodal analysis of the circuit.

$$\Delta U = K\Delta E' \qquad (19)$$

Applying equations which are derived in detail in [20], the result is a matrix expression such as

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ \vdots \\ x_i \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} A_{1,1} & \dots & A_{1,2} & \dots & A_{1,n} \\ \vdots & \dots & \vdots & \dots & \vdots \\ A_{i,1} & \dots & A_{i,i} & \dots & A_{i,n} \\ \vdots & \dots & \vdots & \dots & \vdots \\ A_{n,1} & \dots & A_{n,i} & \dots & A_{n,n} \end{bmatrix}\begin{bmatrix} x_1 \\ \vdots \\ x_i \\ \vdots \\ x_n \end{bmatrix} + \begin{bmatrix} b_1 \\ \vdots \\ b_i \\ \vdots \\ b_n \end{bmatrix} \qquad (20)$$

where $\boldsymbol{x_i}$ 3 x 1 vector, $\boldsymbol{A_{i,i}}$ 3 x 3 matrix with parameters of machine *i*, $\boldsymbol{A_{i,k}}$ 3 x 3 matrix that represents the relationship between variables of machine *i* and *k*, $\boldsymbol{b_i}$ 3 x 1 vector.

In [8], more general expressions for this induction generator model are presented. Therefore steady-state situation of (20), for sinusoidal fluctuations of $\Delta P'_m$ can be obtained by superposition. Therefore, for $\Delta E'_r$, $\Delta E'_m$ *and* Δs, the following general expression can be written

$$x(t) = \sum_{i=1}^{n} X_{r,i}\,\mathrm{SIN}(\Omega_{0,i}t) + X_{m,i}\mathrm{COS}\,(\Omega_{0,i}t) \qquad (21)$$

V. CONCLUSIONS

In this paper brief review of load and generation models have been given. The whole next part of this paper was dedicated to wind energy. The paper presents a model of the variable speed wind turbine with PMSG that is scheduled to connect an AC grid through VSC-HVDC. The complete model consists of a PMSG model, a pitch-angled controlled wind turbine model and a drive train model. The generator rotational speed control scheme features the concept of vector control in the dq-synchronous rotating reference frame. MATLAB/Simulink was implemented to build the dynamic model of the wind turbine with PMSG [3]. PMSM model could also be modeled by linearization technique. This proposed method [4],[5], removes the dominant quadratic nonlinearity of the model as well as higher order terms involving the input in the system. Next, a linear dynamic model for an asynchronous wind turbine and for the wind farm with mechanical sinusoidal fluctuation was developed. This proposed linear model presents good accuracy compared to the dynamic model. The proposed model has the following advantages: 1) it has low complexity; 2) it permits modal analysis, direct solution of differential equations, and easy implementation in several conventional tools for power system analysis (load flow analysis and power system stability) [8].

Future of power generation which is cleaner and more efficient to meet the targets of the Kyoto protocol is a head of us. Therefore, it is needed to address new challenges for a network design, operation and modeling of a power system is required of utmost importance.

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BIOGRAPHY

Michal Piotr Jankow was born in Wroclaw, Poland, in 1985. He is currently studying for a M.Sc. degree in Control in Electrical Power Engineering at Wroclaw University of Technology, Wroclaw, Poland and for a MEng. degree at Ryerson University, Toronto, Canada. His present interests are wind energy, wind turbines, offshore and onshore wind parks. His also the finalist of the national competition by LOREA'L in the topic: "Applying renewable energy sources in industry".