Electrical Power and Energy Systems 47 (2013) 147–156

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

# Dynamic maximum available power of fixed-speed wind turbine at islanding operation

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A R T I C L E  I N F O

*Article history:*
Received 23 July 2012
Received in revised form 7 October 2012
Accepted 9 October 2012
Available online 5 December 2012

*Keywords:*
Fixed speed wind turbine
Dynamic modeling
Dynamic Maximum Available Power (DMAP)

A B S T R A C T

Increasing of wind power penetration at power systems requires the development of adequate wind turbine models and consequently useful indexes. Among different models, dynamic model has an important role as a fundamental part of wind farms for representing the dynamic behavior of wind farms at different operating conditions. In this paper, a suitable dynamic model is introduced for wind farms with fixed speed wind turbines. This model is proposed by aggregating the individual wind turbines into an equivalent wind turbine model that operates on an equivalent wind farm electric network. Thus, the system under study is modeled by a set of dynamic and algebraic equations. Based on proposed dynamic model a useful novel index is introduced for calculation of the injection power ability of the wind farm that is an urgent issue in the planning and operating of wind farms. This index is named Dynamic Maximum Available Power (DMAP). In addition, sensitivity analysis of DMAP with respect to effective parameters is carried out and the results are shown.



## 1. Introduction

Wind power is the world's fastest growing energy source with an average growth over the past 7 years of 26% and a foreseeable penetration 12% of global electricity demand by 2020 [1]. Increasing of wind farms penetration on power systems justifies the need for development of accurate wind turbine model, evaluating their influence and thus improving the planning and operation of electrical network.

One type of the used wind farm in power systems is based on fixed speed wind turbines with directly grid coupled squirrel cage induction generator (SCIG) connected to the wind turbine rotor through gearbox. SCIG presents very small rotational speed variations because of the only speed variations that can occur are changes in the rotor slip, and therefore these wind turbines are considered to operate at fixed speed.

The wind farms with fixed speed wind turbines are also consisted of a large number of compensating capacitors, operating on an internal electrical network in order to provide reactive power requirements of SCIGs and improving the power factor.

The dynamic behavior of wind farms has been usually represented by a detailed model, including the modeling of all wind turbines and the internal electrical network [2–5]. Nevertheless, Wind turbines are often connected to small power systems (known as micro grid or MG), operating in parallel to diesel generators. The main objective is always to maximize the wind penetration, while maintaining an acceptable level of service quality to the consumers and ensuring good dynamic response characteristics and a sufficient stability margin during disturbances [6]. A variety of operating and control problems associated with the wind–diesel systems have been identified and studied in the relevant literature. Each type of problem requires a different modeling approach and poses widely varying analysis requirements [6]. The modeling and analysis of the dynamic behavior of wind–diesel power systems has been the subject of numerous publications (e.g. [8–17]), dealing both with small autonomous installations and relatively larger systems, comprising a conventional power station and multiple wind turbines or wind farms.

Previous publications have proved that injection power ability of wind farm is an urgent issue in the planning and operation of wind farms [18–23]. A number of research results show that the maximum injection power is not only determined by wind farm operating characteristics and regulation capacities of other conventional generators, but also related with the system structure, system operating modes and many other factors [24]. To develop insight into system dynamic behavior, it is of considerable benefit to have an efficient analytical dynamic model of the system. The main contribution of this paper is to develop such a dynamic model and then introducing a suitable new dynamic index namely DMAP.

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0142-0615/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2012.10.028

In this regard, the rest of this paper is organized as follows. In Section 2, the study system is introduced and dynamic model of whole system is proposed by aggregating the individual component models. Based on proposed model, a set of differential–algebraic equations (DAE) is obtained at Section 3 and validation of proposed model is confirmed by simulation. In Section 4, by using of proposed dynamic model, dynamic maximum available power (DMAP index) is introduced and formulated. Eigenvalue sensitivity analysis is used to find participation factors in Section 5. Section 6 gives the conclusions.

## 2. System components and modeling

The fixed speed wind turbine is composed of a directly grid coupled squirrel cage induction generator connected to the wind turbine rotor through a gearbox. The rotor limits the power extracted from the wind by using the blade pitch angle (pitch regulated wind turbine) to decrease the rotor aerodynamic efficiency for high wind speeds and thus limiting the mechanical power extracted from the wind.

The general sample system configuration is shown in Fig. 1. The sample system consists of a wind farm with fixed speed wind turbines implemented with SCIG that are connected to the rest of system through a short transmission line. Compensating capacitor bank and local load are connected to the wind farm bus and local load bus respectively. Multiple wind turbines in the wind farm are required to aggregate. For the dynamic stability study, an aggregated model is sufficient to represent the entire wind farm at point of common coupling. In addition, it is desirable to model the rest of micro grid by an equivalent synchronous generator. Thus, the sample system is reduced to two machines system. Study system elements are modeled in next sections and their parameters are brought in Appendix A.

## 3. Wind turbine model

The behavior of wind turbine can be represented by modeling the rotor and drive train. Applying the actuator disk theory [21–23,25], the rotor model provides the aerodynamic torque extracted from the wind by the following equation:

$$T_w = \frac{1}{2}\rho\pi R^3 V_w^2 \frac{C_P(\lambda,\beta)}{\lambda} \quad (1)$$

where $\rho$ (kg/m$^3$) is the air density, $R$ (m) is the rotor disk radius; $V_w$ (m/s) is the wind speed and $C_p(\lambda,\beta)$ is the power coefficient which is a function of the tip speed ratio $\lambda$ and the blade pitch angle $\beta$ for pitch regulated wind turbines that is supposed in this paper [25]:

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \quad (2)$$

where

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3+1} \quad (3)$$

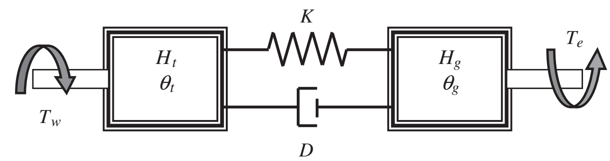


**Fig. 2.** Drive train model.

### 3.1. Drive train model

The drive train model is usually represented by two masses [26,27] as shown in Fig. 2.

The first mass stands for the wind turbine rotor (blades, hub and low-speed shaft), while the second mass stands for generator rotor (high-speed shaft). The equations of the two-mass model in per unit are given here:

$$2H_t\frac{d}{dt}(\omega_t) = T_w - K(\theta_{tg}) - D(\omega_t - (1-S)\omega_S) \quad (4)$$

$$-2H_g\omega_s\frac{d}{dt}(S) = K(\theta_{tg}) + D(\omega_t - (1-S)\omega_S) - T_e \quad (5)$$

$$\frac{d}{dt}(\theta_{tg}) = \omega_t - \omega_g = \omega_t - (1-S)\omega_S \quad (6)$$

where $\theta_{tg}$ is the angle between the turbine rotor and the generator rotor, $\omega_t$, $\omega_g$, $H_t$ and $H_g$ are the turbine and generator rotor angular speed and inertia constant, respectively. $K$ and $D$ are the drive train stiffness and damping constants, respectively. $T_w$ is the torque provided by the wind and $T_e$ is the electromagnetic torque. All parameters are in per unit.

### 3.2. Pitch angle control model

A Proportional–Integral (PI) controller is used to control the blade pitch angle in order to limit the electric output power to the nominal mechanical power. The pitch angle is kept constant at zero degree when the measured electric output power is under its nominal value. When it increases above its nominal value, the PI controller increases the pitch angle to bring back the measured power to its nominal value. The control system is illustrated in Fig. 3.

Where $K_P$ and $K_i$ are the PI controller gains, $P_{ref}$ and $P_{meas}$ are the reference power and output power of wind turbine respectively.

### 3.3. SCIG model

This paper uses a well-known simplified model by neglecting stator flux linkage transients that is common when performing stability studies [27,28]. Thus, the differential equations of induction generator model can be expressed by:

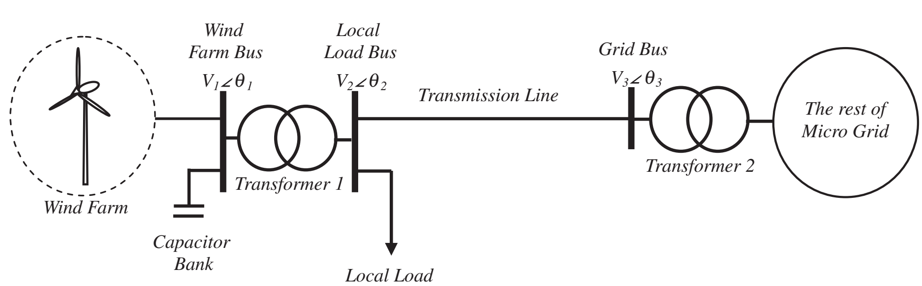


**Fig. 1.** Single line diagram of the sample system.