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Adaptive-tuning of extended Kalman filter used for small scale wind generator control

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ABSTRACT

In this paper a small scale wind generator based on a permanent magnet synchronous machine (PMSM) and associated with an indirect maximum power point tracking (MPPT) algorithm is proposed. Choosing an energy conversion active structure and a sensorless PMSM, to control the system, a speed estimator is required. Facing to other methods, the extended Kalman filter (EKF) model-based estimator allows sensorless drive control in a wide speed range and estimates the rotation speed with a rapid response. The EKF parameters tuning is solved by introducing an adaptive method, *i.e.* adaptive-tuning EKF. This adaptive estimation approach is innovative by using a covariance matching technique. The experimental results prove that the proposed method is technically feasible with good performances within some limits.

1. Introduction

Among the renewable energy sources currently in use, wind turbines have an important role both in their implementation development and in research work. A wind generator converts the wind energy into different forms of electrical energy by means of a wind turbine associated with a power conversion system. Small scale wind generator represents wind generation systems with the ability to produce electrical power smaller than or equal to 30 kW (in Europe) or 100 kW (in the United States). For small wind turbines, two typically-used machines are: the asynchronous machine with squirrel cage [1] and the permanent magnet synchronous machine (PMSM). Due to its easy fabrication, relatively small size and high torque, as well as to avoid the problems of excitation in the classical machines, the PMSM has become more and more widespread [2,3]. With respect to conversion mechanical energy into electrical energy with small scale wind generator, there are two types of structures, the passive one and the active one. The passive structure uses a three-phase diode bridge, which is a non-controllable AC–DC converter [2]. An active structure is obtained by adding a controllable DC–DC converter to the passive structure. Occasionally, an active structure based on a controllable three-phase AC–DC converter is also to be found [2]. The advantages of passive structure are its robustness and its attractive price, but on the other hand, in these structures, the flow of energy is not optimized. The active structure allows this optimization. The mechanical energy extracted from the wind depends on the wind speed, as well as on the ratio between the turbine rotational speed and the wind speed. There is a specific optimal ratio for each wind turbine which is named the optimum tip speed ratio (TSR). The captured power at this ratio is the maximum. As the wind speed is variable, to obtain maximum energy extraction, the rotational speed should be modified; so that the optimum TSR remains constant.

To extract the maximum power and therefore the maximum energy, an algorithm of maximum power point tracking (MPPT) is required [4–6]. Thus, the wind generator is driven by a MPPT seeking in real-time the maximum power point. There are two categories of MPPT methods: the first one is a direct process and the second one is an indirect process. The direct MPPT is based on the perturbation of a variable system and the observation of the system in real-time. The complexity arises when the ratio between the values of perturbation and observation time has to be selected, mainly for systems with a lot of noise. The indirect MPPT method is

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based on iterative search as well as the knowledge of the wind generator parameters [4]. The accurate knowledge of these parameters can often cause additional problems and also requires the use of mechanical sensors such as a speed sensor. To increase the system overall reliability and at the same time to limit the economic cost, for small scale wind generator the mechanical sensor is eliminated [2]. As a result, in several cases, a speed estimator is needed.

Concerning the estimation of the PMSM rotational speed, there have been a number of studies that proposed various methods for this aim. While the estimation method based on observer depends to some extent on the accuracy of the motor model; the extended Kalman filter (EKF) is the most popular model-based estimator allowing sensorless drive control in a wide speed range [7]. The Kalman filter principle introduced by Rudolf Emil Kalman, represents an efficient means for the recursive data processing. Performance of the EKF depends on the correct prior knowledge of the process and measurement noise covariance matrices (Q and R, respectively) [8].

In adaptive Kalman filter, the knowledge about the noise covariance values is adjusted according to the difference between the predicted estimates and the current measurements. Several ways for this purpose have been developed in Refs. [8–10] which can be classified into four categories: Bayesian, maximum likelihood, correlation (autocorrelation) and covariance matching. Few studies have introduced methods either offline or non-adaptive to decide metrics of measurement and state noise covariance for the rotor speed estimation. Authors of [11] gave a comparison between three variants of the square-root implementation for the EKF with the standard implementation that consider the full matrix representation in sensorless control of AC motor drive. The benefits of square-root EKF was discussed for every method and it referred that such methods improved accuracy and robustness in critical operating conditions of the drive whereas its computational cost is higher than the conventional algorithm.

This study focuses on a small scale wind generator based on PMSM with an active structure to maintain the optimum TSR constant. The proposed MPPT is based on the knowledge of the parameters of small scale wind generator as input with EKF-based estimation of mechanical rotation speed. Structured into five sections, the rest of this paper is organized as follows. In Section 2, the model of the small scale wind generator system is presented. The adaptive estimator of the rotation speed is selected and validated in Section 3. Experimental results are given and discussed in Section 4. Finally, conclusions are presented in the final Section.

2. Small scale wind generator system modeling

2.1. Small scale wind generator for local a DC microgrid

Small scale renewable energy sources are often used to form local AC or DC microgrids, containing renewable and traditional power production, storage devices and controllable loads [12–15]. Local microgrids are reliable and efficient options to increase the small scale renewable energy penetration while minimize the energy cost. Therefore, the small scale wind generator studied in this paper is considered as a renewable source to be integrated into a local microgrid.

The system overview of the small scale wind generator for the DC microgrid is given in Fig. 1. The test bench picture associated with this system is also presented in Fig. 1 including the various components which are used. Wind and blades are emulated by a three-phase brushless servomotor (NX430EAJR7000 from Parker) driven by a three-phase industrial inverter (C3S063V2F10 from Parker). This industrial driver is controlled in speed by a dSPACE DS1103 card (controller board for rapid control prototyping). The measurement of the real rotation speed is achieved by a resolver (TS2620N861E11 from Tamagawa). The used PMSM is the same as the one that emulates the wind and the blades. The passive DC–DC stage is a classical three-phase diode bridge (SKD 51/14 from SEMIKRON). Capacitor $C_{BUS} = 1$ mF and inductance $L_{BUS} = 50$ mH (112.5 mΩ) were determined to obtain a good compromise between filtering and system dynamics. Indeed, large values are filtered heavily but will limit the system dynamics. An IGBT module (SKM100GB063D from SEMIKRON) is used as a MPPT converter. It is controlled at 5 kHz by the dSPACE DS1103 card via a driver (SKHI22A) from SEMIKRON. The 1.1 mF capacitor is the bus capacitor of the DC microgrid. The power demanded by the DC microgrid is emulated by a programmable electronic load (PEL, 63202 from Chroma). The DC microgrid can use multiple voltages and the PEL maintains the voltage u constant whatever the operating point of the small scale wind generator.

2.2. Model of the aerodynamic and electrical power

The electrical power recovered by a small scale wind generator comes from the aerodynamic power p_{AERO}:

$$p_{AERO} = \frac{1}{2}\rho\pi R^2 c_P v^3 \quad (1)$$

with ρ, R, c_P and v which are respectively the air density (ρ is kept constant and equal to 1.225 kg/m^3), the blade radius, the wind turbine power coefficient and the wind speed. The coefficient c_P is a function of the TSR ($\lambda = R\Omega/v$). For a three-blade wind turbine, c_P can be interpolated by a 7th-order polynomial function [16]:

$$c_P(\lambda) = \sum_{j=0}^{7} a_j \lambda^j \quad (2)$$

The wind turbine rotation speed Ω is described by the fundamental principle of dynamic rotation:

$$\frac{1}{\Omega}(p_{AERO} - p_{EM}) = J\frac{d\Omega}{dt} + F\Omega \quad (3)$$

with p_{EM}, J and F which are respectively the electromagnetic power, the wind turbine inertia and the viscous damping coefficient. The wind turbine is emulated following the model of Excel 1 designed and manufactured by Bergey. The Excel 1 parameters are listed below [16]:

- blade radius: $R = 1.25$ m;
- interpolation factors of c_P;

$$\begin{aligned} &a_0 = -1.9.10^{-3};\ a_1 = 1.7.10^{-2};\\ &a_2 = -1.8.10^{-2};\ a_3 = 1.65.10^{-2};\\ &a_4 = -3.1.10^{-3};\ a_5 = 2.1.10^{-4};\\ &a_6 = -4.2.10^{-6};\ a_7 = -4.10^{-8} \end{aligned}$$

- wind turbine inertia: $J = 1.5$ kg m^2;
- viscous damping coefficient: $F = 0.06$ Nm/rad.

Fig. 2 shows the experimental evolution of p_{AERO} and p_{BUS} ($p_{BUS} = u_{BUS} i_{BUS}$) based on the mechanical speed n ($n = 60\Omega/2\pi$). To obtain Fig. 2, varying wind speed and u_{BUS} have to be imposed. In Fig. 2, for each wind speed the maximum of p_{AERO} is different from the maximum of p_{BUS}. These differences are due to the losses in the PMSM and the use of a three-phase diode bridge.