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Research Article

Performance Enhancement of an Autonomous Wind Energy Conversion System Based on Artificial Cuckoo Search Algorithm

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Abstract: This study proposed to investigate the application of the Artificial Cuckoo Search (ACS) optimization method on wind energy conversion system control. The problem of regulating standalone wind energy generation unit under severe exogenous conditions of wind speed variation and load demand change is considered. First a generic mathematical model for the proposed generation system is presented. An optimal PID control based on Artificial Cuckoo Search (ACS) algorithm is applied on the system to stabilize the load voltage and the frequency even under turbulence wind condition and diverse load variations. The performance of the wind generation system with the proposed optimal PID control is compared with the case of no control. The simulation results prove that the proposed control technique is feasible for the self-excited induction generator application in remote windy area.

Keywords: Artificial cuckoo search, energy storage system, optimal PID control, SEIG, wind turbine

INTRODUCTION

During the last couples of decades, wind power is turned to be one of the major renewable energy sources in the globe. The development of such technology encompasses both offshore and onshore wind power generation. According to Künneke *et al*. (2015) UK can install up to 675 GW of economically feasible offshore wind. This could provide more than six times the UK's present national electricity demand. This is also true for many countries around the world that enjoy excellent wind energy resources such as Germany, Netherland and Spain. This surge of development is not only based on the utility scale wind farms but also based on the growing penetration of autonomous and hybrid wind energy systems.

The standalone wind energy systems are capable to play an essential role for small scale power generation applications particularly in the remote areas where the possibility to get access to the electrical mains is not feasible because it is not a cost effective solution and where the availability of wind energy resources are much higher than the traditional fossil fuel resources. This technological trend in generation attracts many researchers to focus on developments of various types of standalone wind energy system configurations and resolving technical problems that hinder utilizing such systems in a vast manner (see for instance (Meddouri *et al*., 2015; Kassem and Yousef, 2013)).

In general, the standalone wind energy generation systems either it is autonomous or hybrid system consist of set of interacted electrical equipment that work in a combined fashion to deliver the required output power to the load. Simply these systems comprise of variable speed wind turbine, electrical generator of either induction or synchronous type. This may encompass squirrel-cage, wound-rotor, doubly-fed for induction generator and permanent magnet synchronous generator or synchronous generator with external field excitation. The power generated from any kind of these generators is conditioned through various topologies of AC-DC-AC power electronics converter and then fed to the load. In modern wind energy generation systems, operational characteristics, price and maintenance aspects are among factors that determine the type of generator to be used.

One of the main challenges in operating the standalone wind energy generation systems is regulating the magnitude and the frequency of the load voltage at the output terminal of the inverter side against possible variation in wind speed and load change. These two exogenous inputs are usually treated as unwanted input signals that disturb the system and that need to be suppressed in order to ensure the voltage and the frequency stability. Different control strategies are proposed in literature to enable such generation systems.

In Kassem and Abdelaziz (2015) an induction generator based wind energy generation system is used to feed set of autonomous loads that comprises of three-phase eight resistors bank as a dump load plus resistor and inductor connected in series as a main load through a thyristor based converter. Two PID control loops are proposed in order to regulate the load bus voltage and its frequency. These control objectives were realized by regulating the active power absorbed in the dump load to adjust the system frequency and by regulating the reactive power given by a synchronous condenser to the induction generator for excitation purpose, hence adjusting the voltage magnitude on the load bus.

An optimized PID controller is used in Sebastián and Quesada (2006) to control the output voltage and frequency for autonomous wind energy conversion system at the sending end of self-excited slip-ring induction generator. An ant system algorithm is utilized to search for the optimal parameters of a Takagi Seguno fuzzy system that is in turn produces the optimal gains of the PID controller.

The normal structure of the PID control along with vector control algorithms is also used due to the advantage embedded in the vector control such as the ease to design as well as the inherent ability of separately controlling active and reactive power, hence regulating both the output voltage and the frequency in a very simple way. A rotor flux control was proposed in Idjdarene *et al*. (2007) while a stator flux oriented control was developed in Seyoum *et al*. (2003) these control algorithms are also merged with artificial intelligence technique such as fuzzy control (Meddouri *et al*., 2014) to regulate an isolated generator taking the saturation effect into account. Other control technique such as back stepping control (Nemmour *et al*., 2010) is employed to regulate the DC voltage of the induction generator at the DC link in an standalone wind generation environment.

The wind energy generation system components' in Kassem and Zaid (2014) is almost used as a standalone hybrid generation system where the proposed wind turbine drove a self-excited induction generator.

A different topology that uses autonomous squirrel cage induction generator driven by a wind turbine of variable speed type in a standalone system is introduced in Meddouri *et al*. (2015). This standalone wind generation system successfully utilized a model predictive control technique that is assisted by rotor flux oriented vector control to keep the frequency and the magnitude of the DC voltage at a rectifier side of PWM converter connected to a single capacitor to excite the IG with a battery at constant level.

Among different factors participating in the success of the wind energy generation systems are the arrival of the new power devices technologies, new circuit configurations and novel control strategies.

In this study, investigation of supplying isolated load by hybrid wind/storage generation unit is proposed. Optimal PID controller is used to guarantee supplying the load with voltage which is constant amplitude and constant frequency. The application of power generation systems, remote area is now famous in faraway areas hybrids inclusive the islands which lead to the importance of designing and development of such presented generation system.

SYSTEM MODELING

The proposed wind generation system in this study is designed for standalone applications suitable for remote areas. A self-excited Induction generator driven by a three blade horizontal axis wind turbine is chosen to be the source of power fed to three phase residential loads via an asynchronous AC-DC-AC switched mode power electronics converter. The converter topology is mainly comprised of controlled rectifier, a DC link reactor and a controlled line commutated inverter. A constant voltage constant frequency level required by the load can be obtained at the output terminal of the inverter side by controlling (α_I) the firing angle of the gate turn off thyristor based line commutated inverter. The induction generator variable output voltage and frequency produced by the variable speed wind turbine are rectified by manipulating the firing angle (α_R) of gate turn off thyristor based rectifier circuit.

This complete system model reflects the nonlinear behavioral interaction between different subsystem dynamics such as the induction generator dynamics, the asynchronous AC-DC-AC link and the self-excitation capacitor bank.

The model of the entire WEC system can be divided into several interconnected subsystem models (Fig. 1). These subsystems are the wind turbine, the self-excited induction generator, the rechargeable battery, the buckDC/DC converter, the AC-DC converter and the isolated static load.

WT-Generator model: The WT is characterized by no dimensional curves of the power coefficient C_p as a function of both the tip speed ratio λ and the blade pitch angle β. In order to fully utilize the available wind energy, the value of λ should be maintained at its optimum value. Hence, the power coefficient corresponding to that value will be optimum also.

The ratio of the angular rotor speed of the WT to the linear wind speed at the tip of the blades is defined as the tip speed ratio λ, which is given as follows:

$$\lambda = \omega_t R / V_W \tag{1}$$

where,

R = Rotor radius of the WT

V_w = The wind speed

ω_t = The mechanical angular rotor speed of the wind turbine

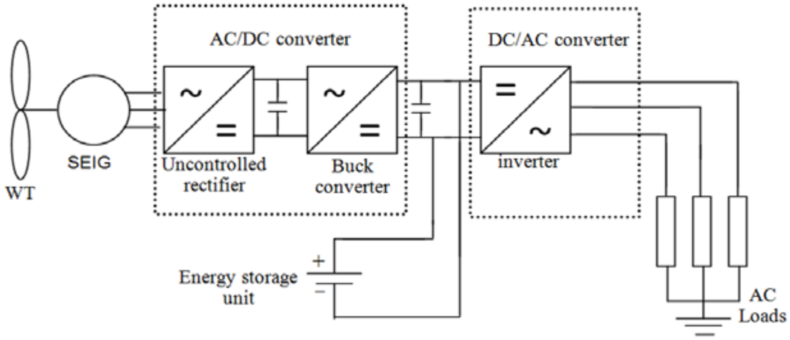

Fig. 1: The layout of proposed autonomous wind generation system with PMPC closed loop control

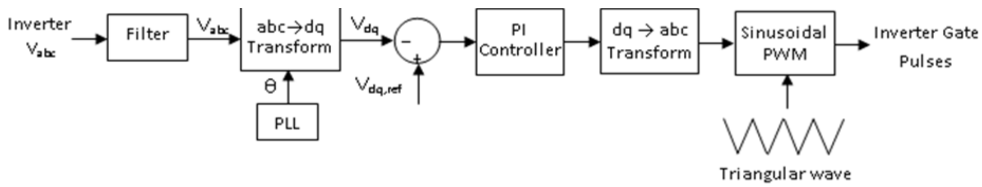

Fig. 2: Inverter controller block diagram

The turbine output power P_t, which is a function of the blade angle, the rotor speed and the wind speed, can be expressed as (Kassem and Zaid, 2014):

$$P_t = \frac{1}{2}\rho A C_p(\lambda,\beta) V_w^3 \tag{2}$$

where, ρ is the air density and A is the swept area by the blades [10, 11], V_w is the wind speed and C_p is the power coefficient of the wind speed, which can be expressed as (Kassem and Zaid, 2014):

$$C_p(\lambda,\beta) = (0.44 - 0.0167\beta)\sin\frac{\pi(\lambda-3)}{15-0.3\beta} - 0.00184(\lambda-3)\beta \tag{3}$$

The induction generator given by the MATLAB/SIMULINK software is used.

Embedded uncontrolled rectifier model: As the wind speed varies with time, the rotor speed of the induction generator varies too. So, the AC output voltage of the induction generator varies in both amplitude and frequency. This un-constant AC voltage is rectified to DC voltage then converted to controlled AC voltage again with constant amplitude and frequency. In this study, an uncontrolled diode bridge rectifier is used to convert the variable output voltage of the induction generator to a variable DC voltage. Supposing that the commutating angle and inductance are negligible, the DC output voltage and current of the rectifier can be given in terms of the rms phase voltage and current of the PMSG respectively, as (Kassem and Hassan, 2012):

$$V_{DC(rect.)} = \frac{3\sqrt{3}}{\pi} V_g \tag{4}$$

$$I_{DC(rect.)} = \frac{\pi}{2\sqrt{3}} I_{g(rms)} \tag{5}$$

Buck DC-DC converter: In this study, the buck DC/DC converter is used. The unidirectional buck converter achieves an interface between the uncontrolled rectifier and the inverter to regulate the transfer of power. The voltage and current relationships between the primary and secondary sides are given by:

$$\frac{V_{rect}}{V_{dc}} = D \tag{6}$$

$$\frac{I_{rect}}{I_{dc}} = \frac{1}{D} \tag{7}$$

D is the duty cycle ratio of the converter.

Battery storage unit: In this study, the battery storage unit includes a single-phase, one arm, IGBT bidirectional inverter and a bank of LAB. The battery is able to supply the power provided to the load by the wind generation system, when the wind speed is too low.

The equivalent electrical model of the LAB contains a controlled voltage source (E_b), connected in series with the internal resistance and the LAB voltage (V_{bat}). It is known that the E_b voltage depends on the charging state and the battery type (Zhang *et al*., 2006).

DC-AC Converter: Figure 2 shows the suggested control involves the manipulation of the modulation index of the reference sinusoidal signal applied to the PWM generator. This is achieved by measuring the 3-φ load voltages through low pass filters, then transforming them to V_{dq} with the help of Phase Locked

Loops (PLL). The measured voltages are compared to the reference voltages that generate the error signals which in turn are fed to PI controllers to generate the reference sinusoidal waves for the PWM generators. The PWM generator is the conventional carrier based modulator that compares the reference sine from the PI controller with a triangular wave to generate the inverter gate pulses.

ARTIFICIAL CUCKOO SEARCH ALGORITHM

ACS optimization is one of the newest and most powerful evolutionary optimization method that presented by Vasanthakumar *et al*. (2015). This approach is inspired by the life of a bird called cuckoo which has been developed by Modiri-Delshad *et al*. (2014). The main merit of Cuckoo Optimization Algorithm (COA) is that only one parameter needs to be tested (Vasanthakumar *et al*., 2015). In the year 2011, ACS is fully examined in more detail by Modiri-Delshad *et al*. (2014). The use of Levy flights as the search method means that the ACS can detect each optimum in the design. It is necessary, for solving the optimization problem, to put the values of the problem variables in an array form. In the COA the name of this array is habitat (Modiri-Delshad *et al*., 2014; Vasanthakumar *et al*., 2015). The following principles are defined before using this approach (Modiri-Delshad *et al*., 2014):

- A random nest is selected by the cuckoos to lay their eggs, however only one egg can be laid by a cuckoo at the same time
- The top quality eggs only can be transmitted to the following generation
- Identifying the number of host nests available
- Revealing a foreigner egg in the collection nests with a probability $\alpha \in [0, 1]$

Selection of appropriate objective function determines the quality of the solution. COA main steps can be expressed as the following (Vasanthakumar *et al*., 2015):

Step 1 : The cuckoo's current habitat is randomly determined.
Step 2 : A number of eggs for each cuckoo is assigned.
Step 3 : Radius of laying egg for each cuckoo is determined.
Step 4 : within nest of hosts, cuckoos lay eggs which are in their radius of laying egg.
Step 5 : Destroying the number of eggs that are identified by the host.
Step 6 : Growing the Cuckoo eggs which have not been identified.
Step 7 : The new habitat of the cuckoo is evaluated.
Step 8 : The maximum number of cuckoos that have any place to live are determined and those which are in the wrong habitats are eliminated.
Step 9 : Cuckoo bloc using the K- means to determine the best set of cuckoos as objective habitat.
Step 10 : Moving the new population of Cuckoo toward the goal habitat.
Step 11 : The target condition is obtained, or go to step number two.

OBJECTIVE FUNCTION

The performance of the optimization approach is forced based on appropriate objective function. In this study, Integral Time Absolute Error (ITAE) is applied as a cost function (J) to properly tune the parameters of the proposed fuzzy PID controller for both DC/DC converter and DC/AC inverter controllers. The main advantages of the ITAE objective function are its more ability to reduce the settling time and the peak value of overshoot compared with the other objective functions. The objective function J based on ITAE technique for both DC/DC converter and DC/AC inverter

Controllers can be expressed as shown in Eq. (8):

$$J = \int_0^t t \left| V_{dc}^* - V_{dc} \right| dt + \int_0^t t \left| V_{dq}^* - V_{dq} \right| dt \qquad (8)$$

SIMULATION RESULTS

Simulation experiments using MATLAB/ SIMULINK environment are performed in this section to study the dynamic response of the autonomous wind generation system under different unbalancing circumstances such as wind speed changes and load variations and to show the effectiveness of the proposed optimal PID control as described in Fig. 3. In this environment, the terminal output voltage and frequency given to the load are chosen to be the controlled variables or outputs of interest. The stabilization of these two variables is achieved under the following specific cases.

Case 1: Turbulent change in the wind speed in case of optimal PID control: In this case the system will be subjected to adverse disturbance conditions by applying turbulent change in the wind speed that ranges from 8.5 m/s to 13.2 m/s as shown in Fig. 4a to 4h. Both optimal PID controllers come to effect and respond to this wind speed disturbance variations. The first controllers regulate the duty cycle of the DC-DC buck converter in such a way that keep both the rotor speed and the rectified output voltage from the converter at approximately constant value despite of the heavily

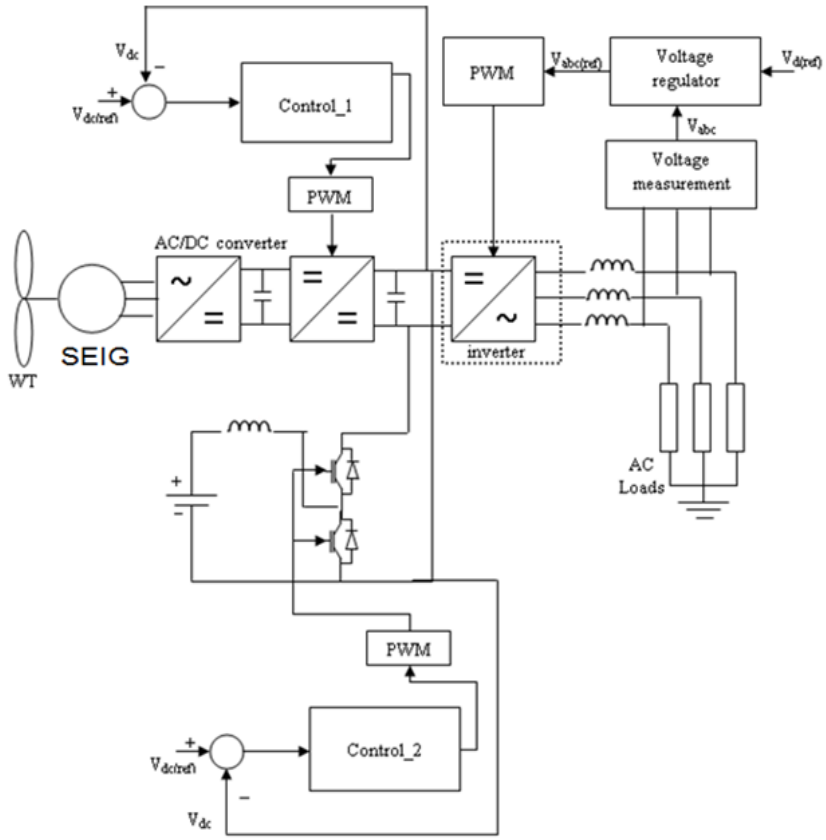

Fig. 3: Autonomous wind/ storage generation unit schematic diagram with the proposed PID control system

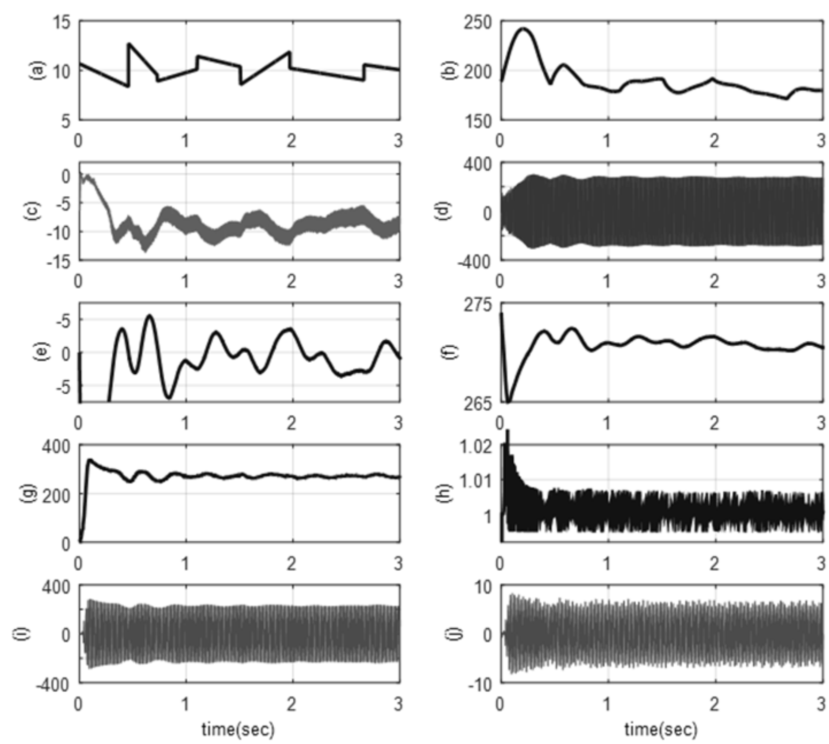

Fig. 4: Proposed system waveforms dynamic responses for wind Speed turbulent Variations based on the proposed optimal PID control; (a): Wind speed (m/sec); (b): IG rotor speed (rad/sec); (c): IG input torque (Nm); (d): IG stator voltage (V); (e): Super capacitor current (A); (f): Super capacitor voltage (V); (g): Inverter DC input voltage (V); (h): Modulation index; (i): Load voltage (V); (j) Load current (A)

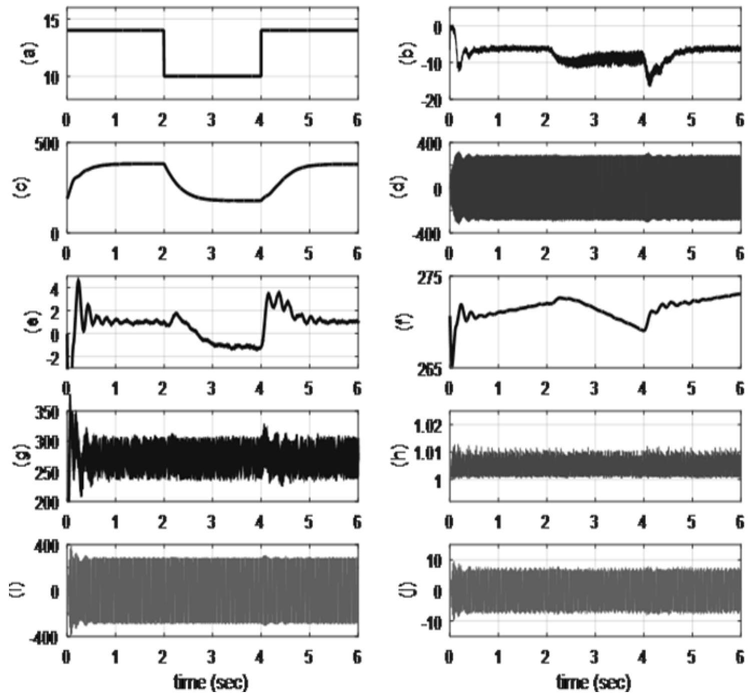

Fig. 5: Proposed system waveforms dynamic responses for wind Speed step Variations based on optimal PID control; (a): Wind speed (m/sec); (b): IG input torque (Nm); (c): IG rotor speed (rad/sec); (d): IG stator voltage (V); (e): IG stator current (A); (f): Inverter DC input voltage (V); (g): Modulation index; (h): Inverter output voltage (V); (i): Load voltage (V); (j): Load current (A)

disturbance fluctuations. While the second controller regulate the modulation index of the inverter and succeeded in constantly regulating the variables at the load side as desired (Fig. 4i and 4j). The uncontrolled rectifier works to convert the variable AC voltage from the induction generator to variable DC voltage that will be stabilized by the used DC-DC buck converter.

Case 2: Step change in the wind speed in case of optimal PID control: In this case the system will be subjected to adverse disturbance conditions by applying step change in the wind speed that ranges from 10 m/s to 14 m/s as shown in Fig. 5a to 5h. The same as case 1, the first controller regulate the duty cycle of the DC-DC buck converter in such a way that keep both the rotor speed and the rectified output voltage from the converter at approximately constant value despite of the heavily disturbance fluctuations. While the second controller regulate the modulation index of the inverter and succeeded in constantly regulating the variables at the load side as desired (Fig. 5i and 5j). The uncontrolled rectifier works to convert the variable AC voltage from the induction generator to variable DC voltage that will be stabilized by the used DC-DC buck converter.

CONCLUSION

This study investigates the optimal PID controller for voltage regulation of an isolated wind generation system. This includes an associated energy storage system, with the role to stabilize the output voltage in autonomous applications. The main contribution of this study is the design of a control strategy which achieves voltage and battery state of charge monitoring, with optimal conditions for battery charging.

Simulations have been carried out to evaluate the effectiveness of the proposed system. The hybrid wind-battery generation system with the proposed controller has been tested through turbulent and step changes in wind speed. The results prove that the proposed controller is successful in maintaining the load voltage of a stand-alone hybrid wind-battery generation system against wind speed excursion. The simulation results also prove that the proposed controller is able to maintain the load voltage at its desired values of magnitude and frequency.

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