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Performance Enhancement of a Wind-driven Fully Superconducting Generator Using PI Controllers

Ragaey A. F. Saleh [1], Noran R. Elkady [2*], and Ragab A. Amer [1]

[1]Department of Electrical Eng., Shebin Elkom Faculty of Eng., Menoufia University, Egypt.
[2]Master of Science Candidate
(Corresponding author: noran.mohamed4453@sh-eng.menofia.edu.eg)

ABSTRACT
This paper investigates the performance of a direct-driven fully superconducting generator (FSG) utilized in wind energy conversion system (WECS) over a wide range of operating conditions. The system under study consists of a FSG driven by a wind turbine and connected to the grid through a back-to-back voltage source converter and a DC link capacitor. The investigation includes studying the effects of wind turbine control systems as well as control techniques for both generator-side and grid-side converters on the system performance. The steady-state performance of the FSG is analyzed with wind speed variation. The system is subjected to various disturbances including 3-phase short circuit fault, line-outage disturbance and step change in wind speed. PI controllers are used to improve the system stability and enhance its performance. The optimal set of the controllers' parameters is obtained using the particle swarm optimization (PSO) technique. Simulation results show that the system performance is well improved with the proposed controllers under various disturbances and operating conditions.

Keywords: *Wind Energy Conversion System; fully superconducting generator; Transient stability; PI controller.*

1. Introduction

The increasing demand for clean, carbon-free electric power, coupled with the worldwide warming crisis, has fueled tremendous interest in the development of renewable energy technologies such as photovoltaic energy, wind energy and geothermal energy, etc. Among the renewable power sources, wind energy has recently gained rapid growth around the world as it is considered one of the important renewable energy resources that provide clean and low-cost power [1]. Wind energy conversion systems (WECSs) are used to produce electricity by converting the kinetic energy created by the wind into electric power. The technologies in WECSs include wind turbines, generators, power electronics and control system technologies [2]. Wind turbines are categorized according to speed-control into fixed and variable speed turbines. Recently, the most applied wind turbines in WECSs are the variable-speed category because of their ability to follow the variation in wind speed to produce the maximum power under the normal operation at slow wind speed (below rated) through MPPT techniques [3]. In case of higher wind speed, the wind turbine generally works under constant power output through either generator load control or pitch control or both if possible [4].

In the initial application of WECSs, fixed-speed induction generators were employed [5]. With the advancement of power electronics technology, variable speed induction generators and synchronous generators have been used [5]. Considerable efforts have been made to develop efficient WECSs worldwide. New technologies in WECSs generators have been invented offering lower weight, higher efficiency and significantly improved reliability [6]. The scientists have suggested the utilization of superconducting generators in WECSs instead of conventional generators. In direct-driven superconducting generators, a high-temperature superconducting (HTS) wire is utilized instead of conventional copper winding on the rotor [7].

The very low resistance of HTS materials directly improves the generation efficiency. Moreover, the generator volume becomes smaller and its weight lighter, thus providing low noise. The magnetic field intensity in the air gap is two times more than that in permanent magnet generators. Therefore, improving the power density by increasing the flux density can increase the rating of wind turbine generators. With recent progress in technologies of AC superconducting wires, it has become possible developing a fully superconducting generator (FSG) [8]. In FSG, HTS wires are used in both rotor and armature windings. In this case, the air gap can be much smaller. This offers more advantages such as higher efficiency and energy saving and reduced size, weight, oil consumption and CO_2 emission. Estimates demonstrate that a 10 MW FSG would weigh about one-third the weight of a conventional generator with the same power rating [9].

This reduction in weight would also allow an increase in blade size and greater power output. The net effect is expected to double the power capacity of conventional systems and lower the cost of generated wind energy. However, FSG suffers from instability when connecting to the grid due to the absence of damping elements, the matter that adversely affects the transient performance of these machines [10]. Moreover, the extremely long time constant of the superconducting winding makes the FSG response slow so it needs more attention to enhance its performance. Up till now, no work has been published in the literature regarding studying the performance of FSG in WECS.

In this paper, a complete model of a 2 MW FSG driven by a wind turbine is developed. The system performance is investigated and analyzed under various operating conditions. Proper PI controllers are designed using PSO technique to stabilize the system and enhance its performance.

2. System Description

The system consists of FSG driven by a wind turbine. The generator is connected to the grid through a full-scale power converter and has a back-to-back voltage source converter and a DC link capacitor as shown in Figure (1). The back-to-back converter consists of a rectifier and an inverter. Both rectifier and inverter consist of multilevel IGBT-controlled switches. The rectifier is called a generator side converter, being able to control the torque and speed, while the inverter is called a grid side converter keeping the voltage in DC-link constant [11]. The mathematical model of the wind turbine and generator is given in the appendix.

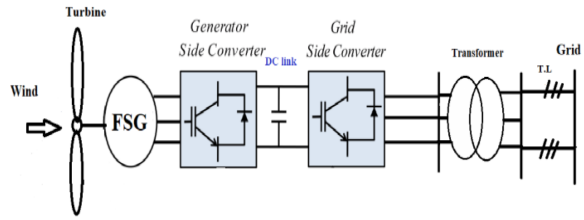
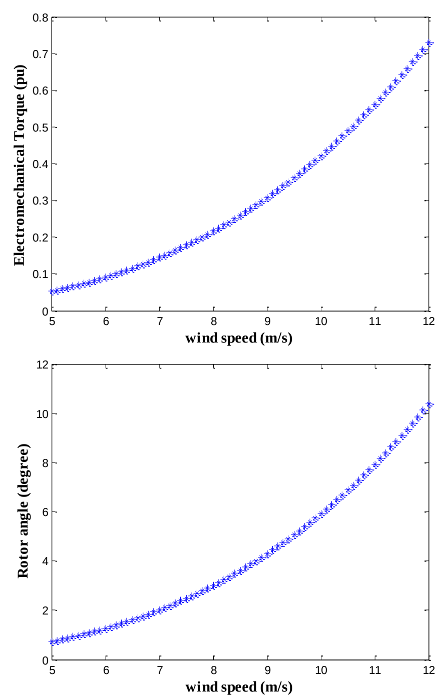


Figure 1- Schematic diagram of the considered WECS

3. Steady-state performance

The WECS differs from the conventional power system. In the conventional power plant, the generated power can be adjusted by controlling the steam that drives the prime mover (governor control). On the other hand, the extracted power from the WECS fluctuates with the wind speed [12] .This nature was the motivation for the researchers to develop various approaches for the investigation of WECS behavior. This paper implements a steady-state analysis of variable-speed WECS that includes FSG. The results are investigated in Figure (2).

The system performance is analyzed during the variation of wind speed from 5 m/s to 12 m/s as a suitable range of operation. It is noticed from these results that, as wind speed increases, electromechanical torque, the generated power and rotor angle increase, while, the stator flux decreases over the same range of operation. These results are logical.



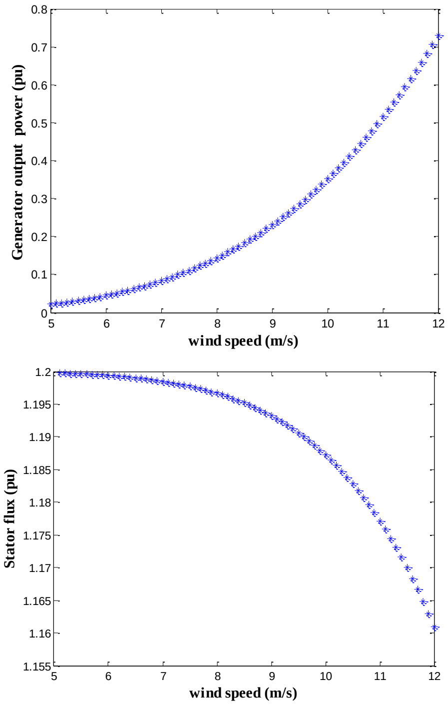


Figure 2- Steady-state characteristics of FSG with variable speed WECS

4. Dynamic analysis

In this section, the system response is studied under different transient conditions; namely 3-phase short circuit fault, one line-outage fault, and under a change in the wind speed. MATLAB/SIMULINK model of the considered system is shown in Figure (3).

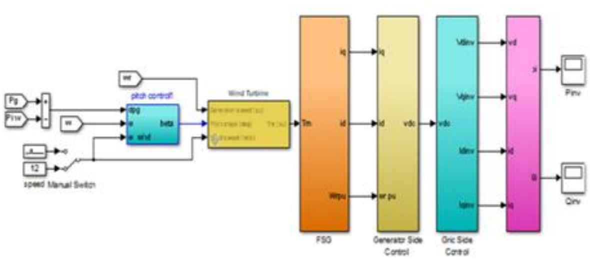


Figure 3- System configuration in MATLAB/SIMULINK

4.1 Proposed control system design

It is well known that WECS needs good control systems to reduce wasted power. The system is equipped with a number of control schemes; pitch angle control, generator side control and grid side control. The aerodynamic efficiency of a wind turbine is strongly influenced by the variations of the pitch angle with respect to the plane of rotation. Pitch control is utilized at high wind speeds greater than the rated speed (12m/s) to limit the power within rated values. The pitch angle should be changed to balance the electrical and mechanical power. Pitch angle is controlled by servomotor controlled by PI controller. The model of the pitch angle controller is shown in Figure (4).

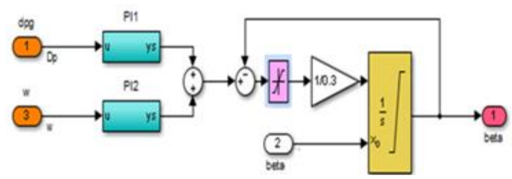


Figure 4- Pitch angle control system model

The generator side control is utilized for maintaining the desired rotor speed. The reference speed used is assumed to be set at the optimal speed to obtain the maximum power in a certain wind speed, while the grid side converter control technique implements current controllers to regulate the extracted power of the wind turbine system so that the DC link voltage stays constant [11]. Fully decoupled control is applied between the generator side and grid side converters. The current controllers compare the generated reference current to the actual grid current. PI controllers are utilized to provide suitable performance to the system in various operating conditions. PI controller consists of a proportional gain besides an integrator gain, where the proportional gain improves the response and stability of the system, the integral gain when added to proportional gain speed up the movement towards the set point and reduces the steady-state error. Two PI controllers are used for pitch angle control, two PI controllers are used for generator side converter and two PI controllers are used for grid side converter. However, this technique does not effectively manage during fault conditions due to difficulties in tuning the PI parameters. There are many optimization techniques that have been used widely in control systems design. Among these techniques is the PSO algorithm which has gained great interest. PSO is used to get the optimal setting of PI controllers used in generator and grid side converters. The fitness function of the PSO technique is shown in an appendix. Table (1) shows parameters of PI controllers obtained by the PSO algorithm. The simulation models of generator side converter and grid side converter are shown in Figure (5) and Figure (6) respectively.

Table 1- PI controllers parameters

	Technique PSO	
Parameters	K_p	K_I
PI Controller#1 Generator side control	0.0357	–0.1019
PI Controller#2 Generator side control	0.0357	–0.1019
PI Controller#3 Grid side control	0.1339	-4.54×10^{-6}
PI Controller#4 Grid side control	0.1339	-4.54×10^{-6}

From Table (1), it is noticed that the integral gains of PI controllers in Grid side control are approximately zero so that P controller can be used instead of PI controller in Grid side control.

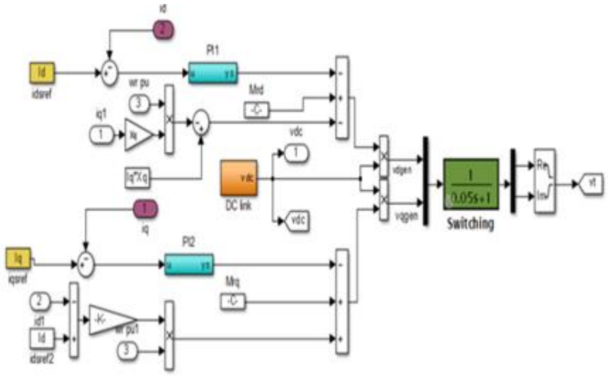


Figure 5- Simulation model of generator side control with PI controller

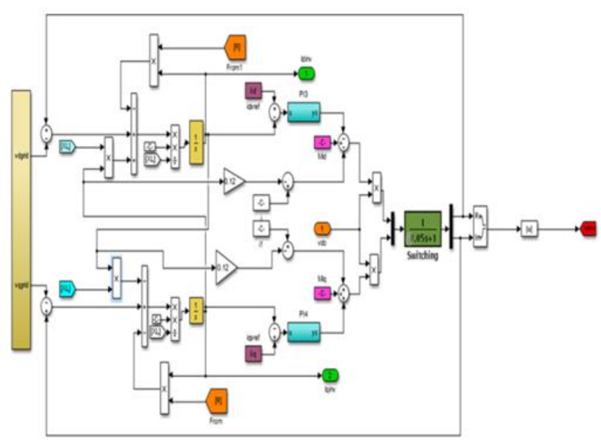


Figure 6- Simulation model of grid side control with PI controller

4.2 Simulation Results

System response to short circuits with the proposed control systems is shown in Figure (7). Firstly, the system was running at steady-state operation for 0.5 sec. Then, it was subjected to a short circuit fault at the high voltage side of the transformer for 100 ms.

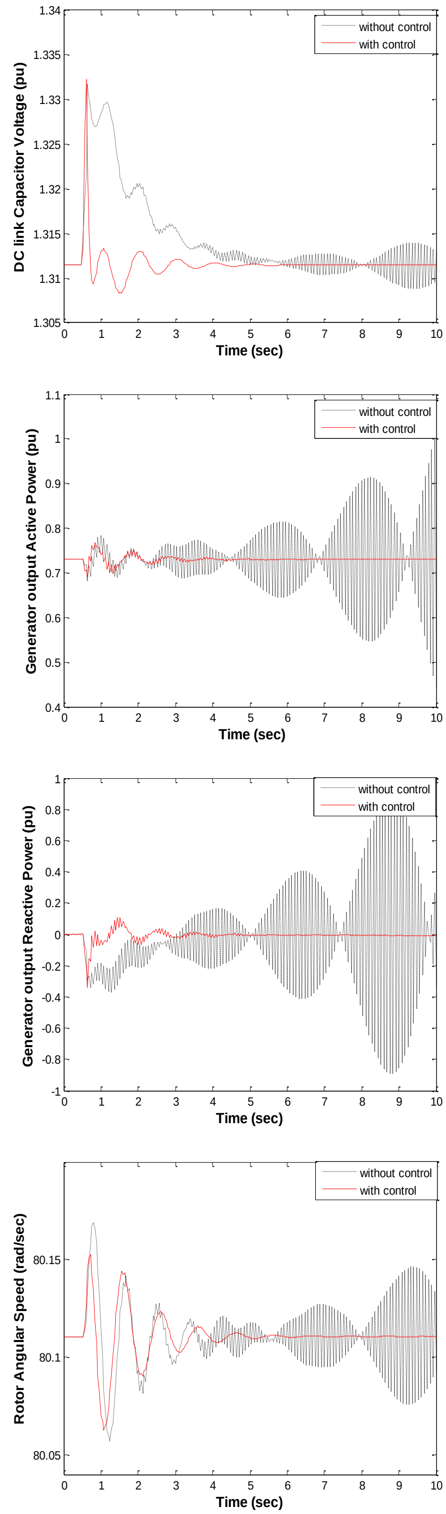


Figure 7- Transient response to a 3-phase short circuit fault

System response to one line outage with the proposed control system is given in Figure (8). Firstly, the system is running at steady-state operation for 0.5

sec. Then, it is subjected to one line outage for 100 ms.

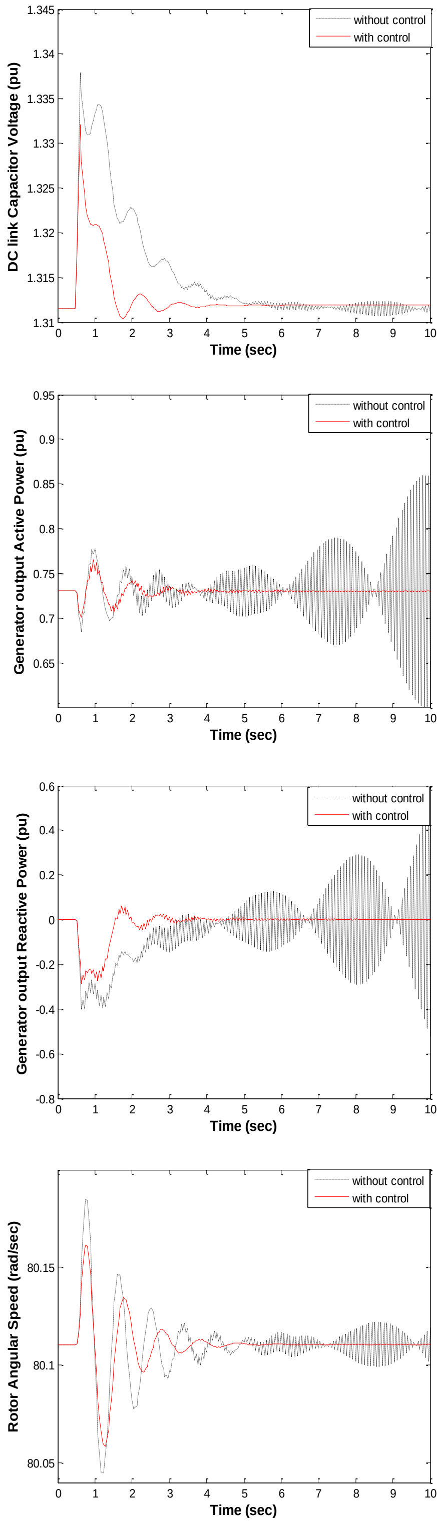


Figure 8- Transient response to one line outage condition**.**

System response to speed change with the proposed control system is shown in Figure (9). Firstly, the system is running at steady-state operation for 0.5 sec. Then, it is subjected to increase speed from rated speed of 12 m/s to 13 m/s for 500 ms.

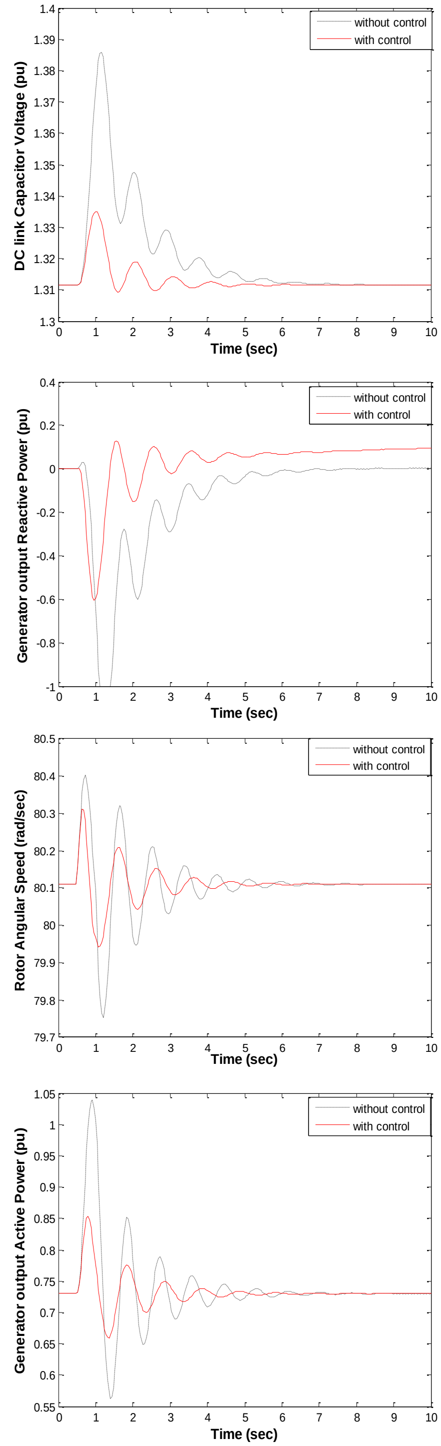


Figure 9- Transient response to step increase in wind speed

Simulation results with the proposed control system indicate that both first swing and settling time of DC-link capacitor voltage, generator output active power, generator output reactive power and rotor angular speed are reduced compared to results without generator and grid side control. Thus, the results illustrate superior performance with the proposed control technique and form a useful guide to improve the performance of WECS under wide range of disturbances.

5. Conclusions

In this paper, PI controllers are developed to stabilize a fully superconducting generator (FSG) directly-driven by a wind turbine and connected to the grid through back-to-back converter and DC link capacitor. PSO technique is used to select a set of control parameters that give an optimal performance at various transient conditions. The considered system is simulated using MATLAB/SIMULINK toolbox. Wind turbine control systems are included as well as control techniques for both generator-side and grid-side converters. The system performance is presented with the proposed topology under short circuit fault, one line outage and step increase in wind speed conditions in comparison with its performance without generator and grid-side control. Simulation results show the effectiveness of the proposed controllers to improve the considered system stability and enhance its performance during various disturbances.

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7. Appendix

The mathematical model of the FSG [10]:

$p\psi_f = \omega_o [v_f - i_f R_f]$ (A.1)

$p\psi_d = \omega_o [v_d + \psi_q] + \psi_q \ \omega$ (A.2)

$p\psi_q = \omega_o [v_q - \psi_d] - \psi_d \ \omega$ (A.3)

$p\delta = \omega$ (A.4)

$p\omega = \frac{\omega_o}{2H} [T_m - T_e]$ (A.5)

$T_e = \psi_d i_q - \psi_q i_d$ (A.6)

The mathematical model of the power extracted from wind turbine [13]:

$P = 0.5\rho \pi r^2 V^3_W C_p$ (A.7)

$C_p(\lambda, \beta) = C_1 \{(C_2 \frac{1}{\lambda_i}) - C_3 \beta - C_4\} e^{-C_5 \frac{1}{\lambda_i}} + C_6 \lambda$ (A.8)

Fitness function of PSO technique:

$J = w_{1*}\Delta Q_g + w_{2*}\Delta V_{dc}$ (A.9)

where, ΔQ_g and ΔV_{dc} are the generator reactive power and DC link voltage deviations w.r.t the initial values (Q_{g0}=0 p.u, V_{dc0}=1.311 p.u)

Parameters of the studied system are:
S=2 MVA, H=3.5 sec,
L_f=0.42p.u, L_d=L_q=0.35p.u, M_{fd}=0.35p.u
R_f=0.0000029 p.u, R_E= 0.01p.u, L_E= 0.12p.u

Wind turbine parameters:
r =60m, ρ = 1.225 kg/m^3, V_W (Rated)=12m/s, C_1= 0.5176, C_2= 116, C_3= 0.4, C_4= 5, C_5= 21, C_6=0.0068

Parameters of PI controllers used in pitch angle control system
K_{P1}= 3, K_{I1}= 30, K_{P2}= 150, K_{I2}= 25

8. List of symbols

P : derivative operator w.r.t time
R_f : resistance of field winding
L_f : self-inductance of field winding
M_{fd} : mutual inductance between armature and field windings
L_d, L_q : self-inductance of armature winding in d,q axis respectively
V_f : field voltage
V_d : d-axis stator voltage
T_m : mechanical torque ψ : flux linkage
V_q : q-axis stator voltage
T_e : electromagnetic torque
i_f : field current
R_E : total resistance of transformer and transmission lines
L_E : total inductance of transformer and transmission lines
δ : rotor angle with respect to infinite bus
ω : FSG speed deviation from synchronous speed
H : inertia constant ω_o : synchronous speed
ρ : air density r : blade radius
V_w : wind speed C_p : power coefficient
β : pitch angle in degrees λ : tip speed ratio.
w_1, w_2 : PSO constant weights