Optimal Controller Design for Wind Turbine using Sliding Sector and Genetic Algorithms

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Abstract. This present work presents a major contribution to the field of wind turbine control which is the more challenging context that this paper is focused. This manuscript gives a novel design of a high-performance controller using the sliding sector law optimized by genetic algorithms. This developed design gives an improvement in the robustness of wind energy systems compared to the traditional law known as sliding mode control (SMC). The proposed design is based on the idea of extending the SMC by transforming the sliding surface into a sliding sector. Genetic algorithms are used to optimize the switching gain in its control structure in real-time. The benefits of this design under fast and random wind speed variations are utility for non-linear systems, achieving maximum power tracking, ensuring robust stability, eliminating the chattering problem, and faster response time. The strengths of this design are proved by simulation results of the main parameters of the two-mass model of wind turbines using Matlab software.

Keywords: *Optimal control, Sliding sector, Variable speed wind turbine, Genetic algorithms*

1 Introduction

The field of Energy Engineering has taken much interest in recent decades. This area motivates researchers to find new sources of clean, sustainable, and renewable energy [1, 2]. In addition, this field motivates engineers to develop new strategies for these installations. The main goal behind these intensive studies is the production of electricity in a clean way without harming our planet while retaining primary resources to live better on Earth.

Among the most attractive clean and renewable energy sources are wind energy conversion systems. Wind turbines are promising and attractive alternatives for the production of electricity [3]. It is therefore very interesting to do studies and research that give control law syntheses for variable speed wind turbines (VSWT) in order to achieve good performance for these systems. This paper focuses on this context of more complicated control laws of VSWT. In this article, design a high-performance controller using the sliding

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sector control law based on genetic algorithms (GAs). The design proposed in this document is an extension of the traditional sliding mode control (SMC) law by converting the sliding surface into a sliding sector as in [4]. The utility of the classic SMC law is very powerful for VSWT [5] but it has a major drawback known as the chattering phenomenon [6]. The problem of chattering is caused by the use of a high gain in the case of strong disturbances and great uncertainties, this drawback can cause rapid variations of the control signal and damage to the system because of high-frequency oscillations [7, 8]. The elimination of chattering is the important reason that leads to this contribution of this paper that deals with the SMC law developed. The proposed law retains the advantages of the SMC law and gives new benefits such as the elimination of chattering, accurate tracking, faster response time, and the use of a high gain. GAs are introduced to optimize switching gain automatically by imitating the process of natural selection observed in Darwin's theory of biological evolution [9].

This paper contains five sections. Section 2 presents the mathematical model of the mechanical part of the wind turbine. Section 3 gives the new law control of wind turbines. The effectiveness of this developed control law is proven by simulation results obtained by the Matlab toolbox in Section 4. Section 5 summarizes the main points of this paper.

2 Wind power system model

In the context of controlling the three-blade horizontal axis variable speed wind turbine (VSWT), the mechanical subsystem is considered which is represented by two-mass because it is the most adopted model as depicted in Figure 1. A systematic analysis and calculation of the dynamic behavior of the mechanical subsystem of the VSWT is represented by the following matrix in state space in Eq.1. This matrix provides insight into the response of the mechanical two-mass model of the VSWT under different operating conditions and control inputs [10, 11]. The input and the output of the wind power are respectively generator torque and the rotor speed. The important factors are presented in Table 1.

$$\begin{pmatrix} \dot{\omega}_r \\ \dot{\omega}_g \\ \dot{T}_{ls} \end{pmatrix} = \begin{pmatrix} -\frac{K_r}{J_r} & 0 & -\frac{1}{J_r} \\ 0 & -\frac{K_g}{J_g} & \frac{1}{\eta_g J_g} \\ B_{ls} - \frac{K_{ls}K_r}{J_r} & \frac{K_{ls}K_g}{\eta_g J_g} - \frac{B_{ls}}{\eta_g} & -K_{ls}\frac{J_r+\eta_g^2 J_g}{\eta_g^2 J_g J_r} \end{pmatrix} \begin{pmatrix} \omega_r \\ \omega_g \\ T_{ls} \end{pmatrix} + \begin{pmatrix} \frac{1}{J_r} & 0 \\ 0 & -\frac{1}{J_g} \\ \frac{K_{ls}}{J_r} & \frac{K_{ls}}{\eta_g J_g} \end{pmatrix} \begin{pmatrix} T_a \\ T_{em} \end{pmatrix} \quad (1)$$

Table 1. Wind turbine notations of the various coefficients.

Factors	Notation	[Unit]	Factors	Notation	[Unit]
Blade radius	R	[m]	Rotor external friction	K_r	[N.m.rad^{-1}.s]
Air density	ρ	[Kg.m^{-3}]	Low shaft torque	T_{ls}	[N.m]
Gearbox ratio	n_g	Unitless	Slow shaft torsion	B_{ls}	[N.m. rad^{-1}]
Power Coefficient	C_p	Unitless	Slow shaft friction	K_{ls}	[N.m.rad-1.s]
Tip speed ratio	λ	Unitless	Fast shaft torque	T_{hs}	[N.m]
Wind speed	v	[m.s^{-1}]	Generator speed	ω_g	[rad. s^{-1}]
Aerodynamic torque	T_a	[N.m]	Generator inertia	J_g	[Kg.m^2]
Rotor speed	ω_r	[rad. s^{-1}]	Generator external friction	K_g	[N.m.rad^{-1}.s]
Rotor inertia	J_r	[Kg.m^2]	Generator torque	T_{em}	[KN.m]

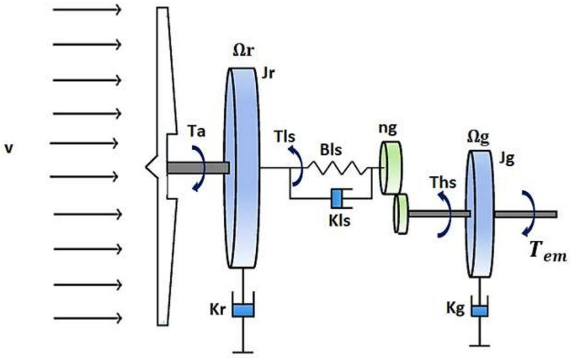


Figure 1. Wind turbine's two-mass mechanical model.

3 Sliding sector design optimized by genetic algorithms

In order to achieve good performance for VSWT, it is necessary to design a robust controller that ensures optimal tracking of the reference signal, maximum capture of wind energy, reduction in oscillations caused by rapid and random fluctuations in wind speed, and reduction in aerodynamic loads. It is in this context to design a robust controller that this section carries.

The key aspect in designing a robust controller is the selection of a sliding surface that is an attractive surface. The sliding surface expression is based on the system's relative degree [8]. For the wind turbine, the relative degree is equal to 2. In this paper, this sliding surface selection is converted into a sliding sector by dividing it into two sliding sub-surfaces based on the system states and a desired reference signal. Then the expressions of the two sub-surfaces and the sliding sector are given as follows in Eq.2 with k_1 and k_2 are positive constants. However, the entire state space of the wind turbine is divided into three different regions as depicted in Figure 2 and these regions are expressed in Eq.3 noting that $R_{g,3}$ represents the sliding sector.

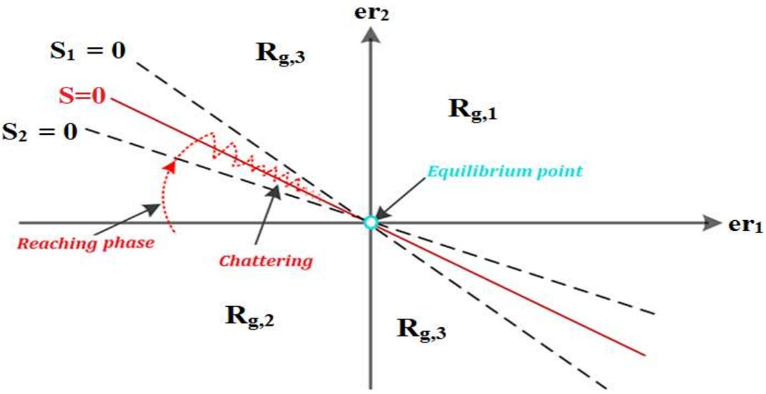


Figure 2. The three regions of the wind power's state space.

$$\begin{cases} S_1(t) = k_1 \times er_1(t) + er_2(t) \\ S_2(t) = k_2 \times er_1(t) + er_2(t) \\ S\,(t) = \frac{S_1(t)+S_2(t)}{2} = k \times er_1(t) + er_2(t) \end{cases} \tag{2}$$

With $er_1(t) = \omega_r(t) - \omega_{ropt}(t)$, $er_2(t) = \dot{er}_1(t) = \frac{der_1(t)}{dt}$, and $k = \frac{k_1+k_2}{2}$.

$$\begin{cases} R_{g,1} = \cap_{i=1}^{2} S_i(t) > 0 \\ R_{g,2} = \cap_{i=1}^{2} S_i(t) < 0 \\ R_{g,3} = \cup_{i,j}^{2} S_i(t) \times S_j(t) \leq 0 \end{cases} \tag{3}$$

The time derivative of the chosen sliding sector is given by Eq.4 with $f(t)$ is the nominal representation of the wind turbines and $g(t)$ is known constant.

$$\dot{S}(t) = k \times \dot{er}_1(t) + \dot{er}_2(t) = k \times \dot{er}_1(t) + f(t) + g(t) \times T_{em} \tag{4}$$

The control law that satisfies the condition $S(t).\dot{S}(t) < 0$ to ensure the existence of a sliding sector control for a sliding sector, is given by Eq.5 as follows:

$$T_{em}(t) = T_{em,eq}(t) + T_{em,d}(t) \tag{5}$$

With: $T_{em,eq}(t) = -\frac{f(t)+k\times er_1(t)}{g(t)}$

And $T_{em,d}(t) = \begin{cases} T_{em,d1}(t) = -\frac{\alpha}{g(t)} \times \sum_{i=1}^{2} sign\big(S_i(t)\big) & if\ error(t) \in R_{g,1} \cup R_{g,2} \\ T_{em,d2}(t) = -\frac{\alpha}{g(t)} \times \frac{\sum_{i=1}^{2} S_i(t)}{\sum_{i=1}^{2} |S_i(t)|} & if\ error(t) \in R_{g,3} \end{cases}$

The sliding sector control law is combined with GAs. The purpose of using GAs is to optimize the switching gain noted by α in order to avoid the manual choice that will be changed until the optimal value of this gain is reached. The GAs use the three essential operators: selection, crossover, and mutation. The most evolutionary steps of GAs are depicted in Figure 3 and are repeated until a specified number of generations is reached and a convergence criterion is satisfied. These steps are driven by a fitness function, which is given by Eq.6 in order to minimize the tracking error [12]. Twenty generations are used in the GAs and four chromosomes are used for each generation. Each chromosome is coded in five bits using binary coding. The type of selection method is roulette wheel selection and the kind of crossover method is multi-point.

$$fitness = \frac{1}{|er_1(t)|} \tag{6}$$

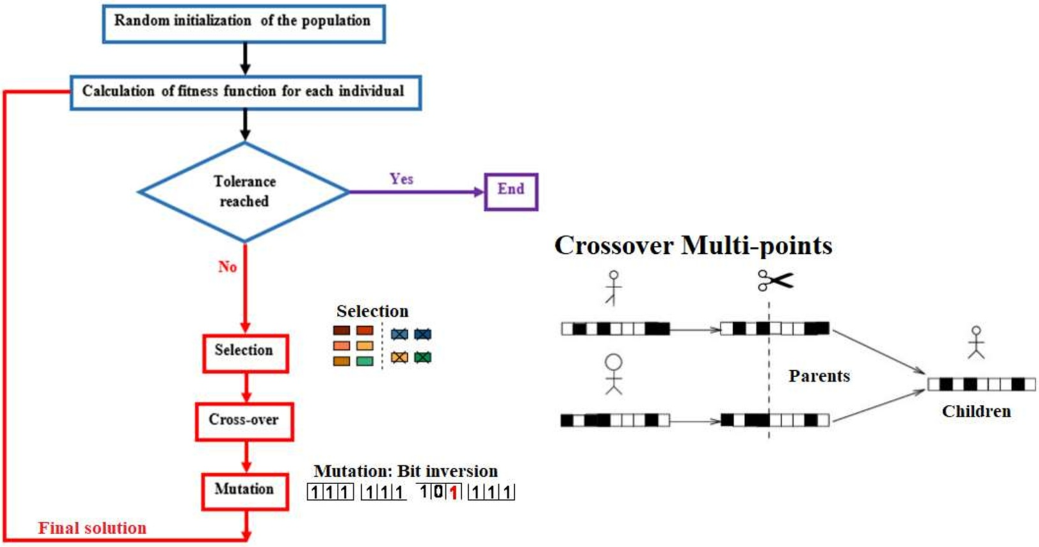


Figure 3. The evolution of genetic algorithms.

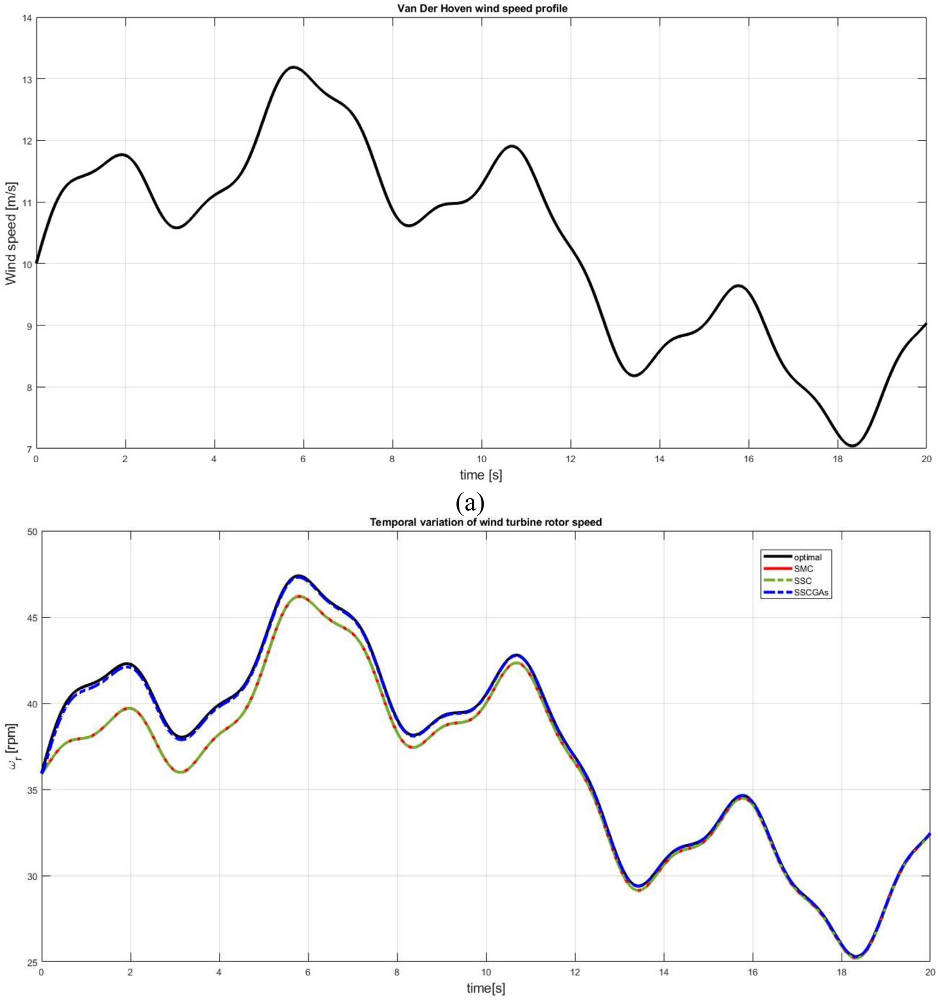
4 Simulation results

The proposed nonlinear law in this paper, which is called sliding sector control based on genetic algorithms (SSGAs), is applied to the mechanical part of VSWT. The values of various parameters are mentioned in Table 2.

Table 2. The various parameters used in the simulation.

Parameter	Notation	[Unit]
R	21.65	[m]
K_r	27.36	[N.m.rad^{-1}.s]
J_r	325000	[Kg.m^2]
K_g	0.2	[N.m.rad^{-1}.s]
J_g	34.4	[Kg.m^2]
B_{ls}	2691000	[N.m. rad^{-1}]
ρ	1.29	[Kg.m^{-3}]
K_{ls}	9500	[N.m.rad-1.s]
k_1	0.3	Unitless
k_2	0.1	Unitless

Figure 4a shows the wind speed profile. Figure 4b presents the curve of variation of the generator torque for the three control laws: SMC, sliding sector control (SSC), and sliding sector control based on GAs (SSCGAs). Figure 4 shows the powerful of the SSCGAs in terms of accurate tracking with a faster response time.

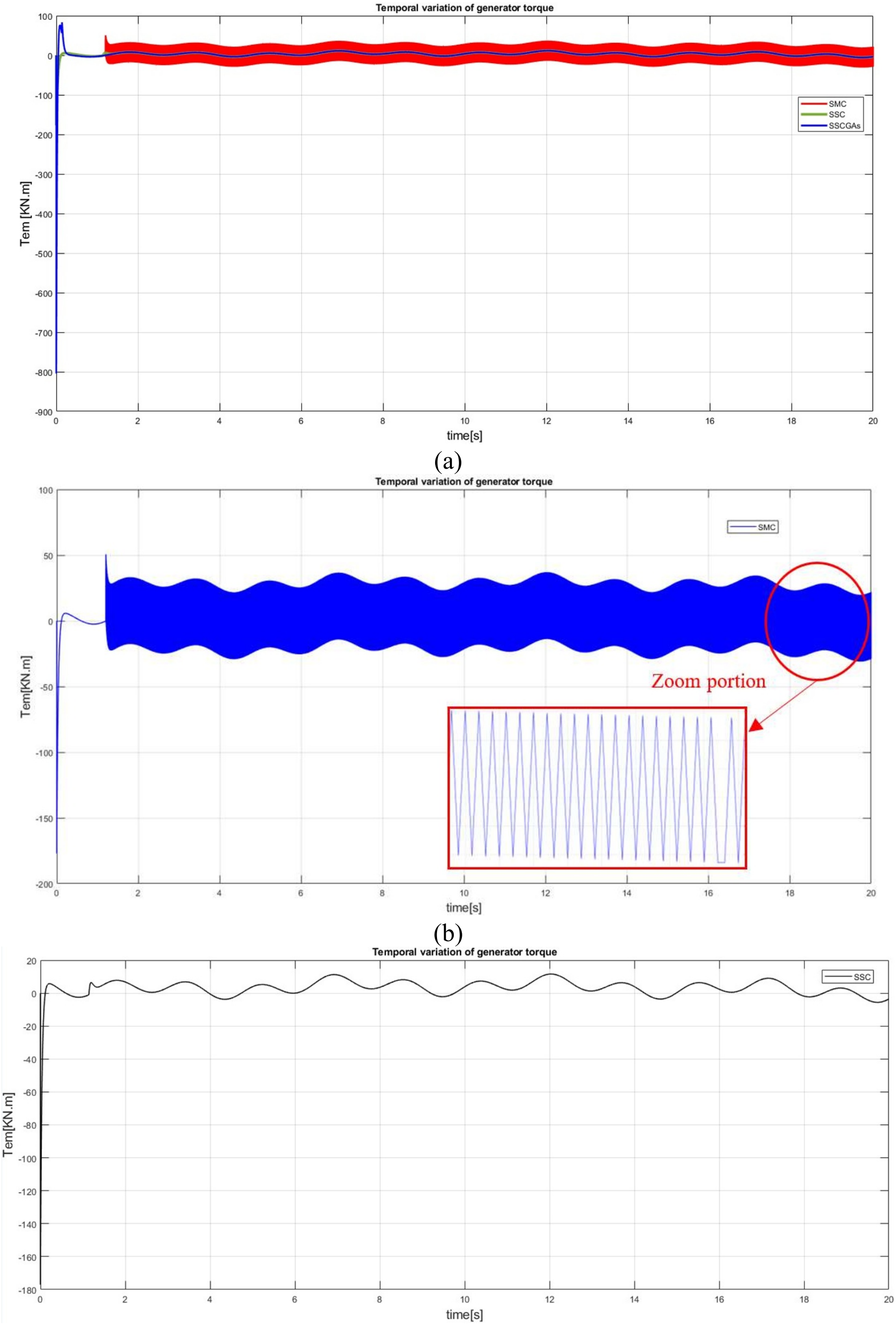


(a)

(b)

Figure 4. Simulation results: (a) for wind speed profile, and (b) for rotor speed.

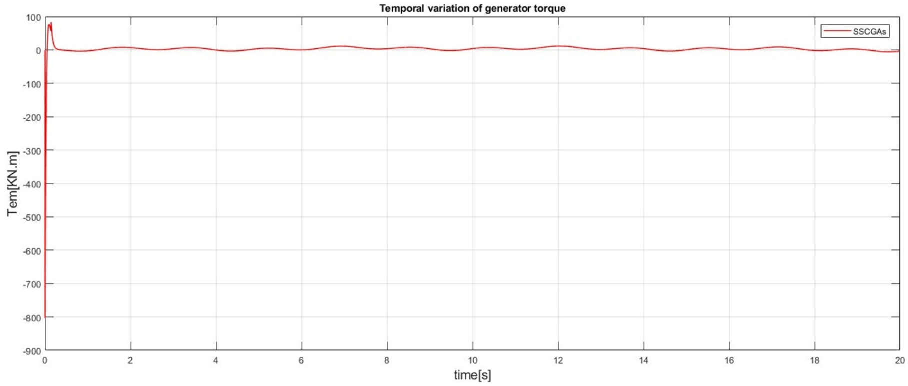
Figure 5a illustrates the variation of wind turbine generator torque for the three laws SMC, SSC, and SSCGAs. Each of these laws is presented in Figure 5b, 5c, and 5d respectively. From Figure 5, this developed law keeps the generator torque constant and that the response time is low also the chattering phenomenon does not exist in this law.


Temporal variation of generator torque
Tem [KN.m]
time[s]
SMC
SSC
SSCGAs
100
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
0
2
4
6
8
10
12
14
16
18
20
Temporal variation of generator torque
Tem[KN.m]
time[s]
SMC
Zoom portion
100
50
0
-50
-100
-150
-200
Temporal variation of generator torque
Tem[KN.m]
time[s]
SSC
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180

(a)

(b)

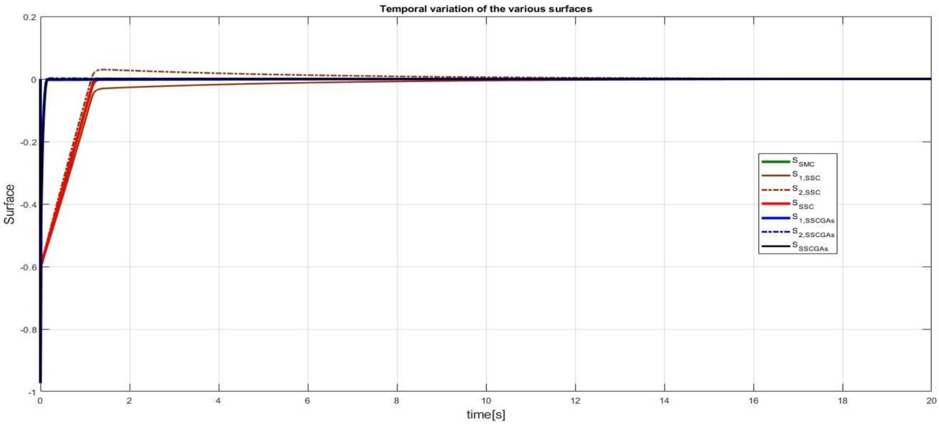
(c)



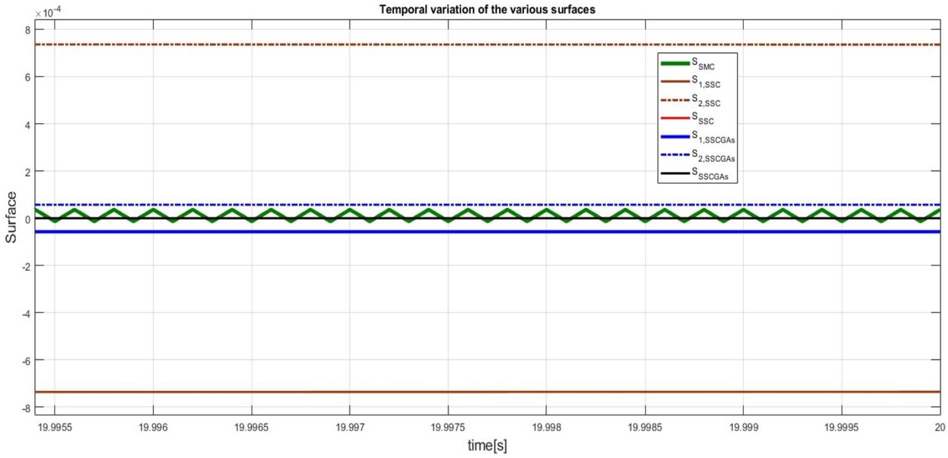
(d)

Figure 5. The variation of wind power generator torque.

Figure 6a shows the variation of the switching surface of the SMC, the variation of the sliding surfaces and their sub-surfaces for both SSC and SSCGAs. Figure 6b is an enlargement of the Figure 6a. The two sub-surfaces of the SSCGAs law rapidly converge towards the sliding sector with a low response time and note that the oscillations do not appear.



(a)



(b)

Figure 6. The variation of switching surface and sliding surfaces.

Figure 7 shows the variation of the switching gain according to number of generations. The switching gain converges to an optimal point which is about 0.6875 from the 17th generation. The switching gain used in SMC and SSC is about 0.5. The values of $k_1 = 0.3$ and $k_2 = 0.1$.

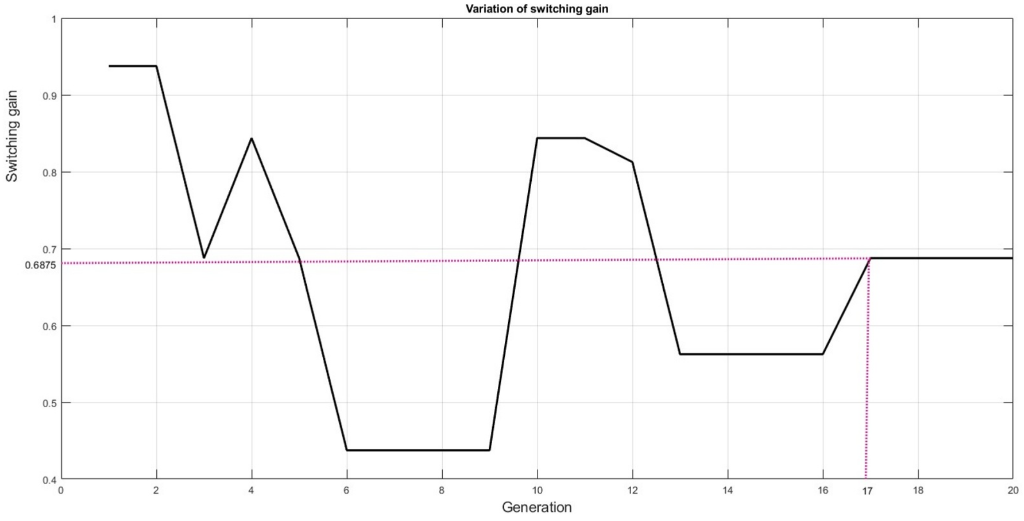


Figure 7. The switching gain variation.

5 Conclusion

This work presents an optimal nonlinear design for high-performance control of variable speed wind turbines. By combining sliding sector control with genetic algorithms to optimize the switching gain, the proposed approach outperforms traditional sliding mode control. Simulation results display its effectiveness in achieving maximum power tracking, robust stability, reduced chattering, and improved response time. This innovative design holds promise for other nonlinear systems and offers practical solutions to real-time challenges in variable-speed wind power.

References

1. Carl R. Shapiro, Genevieve M. Starke, Dennice F. Gayme, "Turbulence and control of wind farms", Annual Review of Control, Robotics, and Autonomous Systems **5** (2022)
2. Mohd Zaidi Mohd Tumari, Mohd Helmi Suid, Mohd Ashraf Ahmad, "A modified grey wolf optimizer for improving wind plant energy production", Indonesian Journal of Electrical Engineering and Computer Science **18** (2020)
3. R. Shafiqur, L.M. Alhems, M.M. Alam, L. Wang, Z. Toor, "A review of energy extraction from wind and ocean: Technologies, merits, efficiencies, and cost", Ocean Engineering, **267** (2023)
4. Y. Berrada, I. Boumhidi, "New structure of sliding mode control for variable speed wind turbine", IFAC Journal of Systems and Control **14** (2020)
5. L.T. Aguilar, D. Jorge, "Analysis and synthesis of sliding mode control for large scale variable speed wind turbine for power optimization", Renewable Energy, **71** (2014)
6. V. Utkin, L. Hoon, "Chattering problem in Sliding Mode Control Systems", VSS'06, (2006)
7. V. Utkin, "Variable structure systems with sliding modes", IEEE Transactions on Automatic Control, **22** (1977)
8. Y. Berrada, I. Boumhidi, "Neural network sliding mode control with time-varying delay for a variable speed wind turbine", International Journal of Power and Energy Conversion, **8**(4), (2017)
9. A. Wright, "Genetic Algorithms for Real Parameter Optimization", Fondations of Genetic Algorithms, **1** (1991)
10. Z. Lahlou, Y. Berrada, I. Boumhidi, "Nonlinear feedback control for a complete wind energy conversion system." Int. Rev. Autom. Control **12**(3), 136, (2019)
11. Y. Berrada, I. Boumhidi, "Sliding mode control for a wind turbine in finite frequency", International Journal of Engineering Systems Modelling and Simulation, **10** (2018).
12. Y. Berrada, E. M. Boufounas, I. Boumhidi, "Optimal neural network sliding mode control without reaching phase using genetic algorithm for a wind turbine", In 2015 10th International Conference on Intelligent Systems: Theories and Applications SITA. 1-6, (2015)