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Double salient switched reluctance generator for wind energy application

Feyrouz Messai [1], Messaoud Makhlouf [1], Houcine Benalla [1] and Abderraouf Messai [2]

[1] Department of Electrical Engineering, Faculty of Engineering Sciences
Université Constantine 1, Route d'Ain El Bey, Constantine, Algeria
[2] Laboratory of electromagnetism and telecommunications
Université Constantine 1, Route d'Ain El Bey, Constantine, Algeria

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Abstract - *A modeling method of switched reluctance generator (SRG) for wind energy applications based on the nonlinear inductance model and electromagnetic field finite element analysis (FEA) has been proposed in Matlab/Simulink environment, the power inverter, excitation source and loads are modeled on Simulink/Simpower system in order to analyze both static and dynamic state. The nonlinear inductance model allows us to develop a control strategy that gives high performance controller with a closed loop was designed on PI controller. Simulation results show the efficiency of the modeling method and validate the applicability of the model.*

Résumé - *Une méthode de modélisation du générateur à réluctance commutée (GRC) pour les applications de l'énergie éolienne sur le modèle de l'inductance non linéaire et champ électromagnétique analysé par éléments finis (AEF) a été proposé dans l'environnement Matlab/Simulink. Le variateur de puissance, source d'excitation et des charges sont modélisés sur Simulink/système Simpower afin d'analyser l'état à la fois statique et dynamique. Le modèle non linéaire de l'inductance nous permet de développer une stratégie de contrôle donnant un contrôleur haute performance à boucle fermée conçu sur le contrôleur PI. Les résultats des simulations montrent l'efficacité de la méthode de modélisation et de valider l'applicabilité du modèle.*

Keywords: Switched Reluctance Generator - Wind Energy - Proportional Integrator + Current Control + Finite element analysis.

1. INTRODUCTION

Due to their several inherent advantageous features such as simple construction, rug, low cost, fault tolerance and robustness and possible operation in high temperatures or harsh environments, switched reluctance generators (SRG) are gaining importance in a wide range of applications such as [1]:

- Renewable energies, in particular wind mills.
- Industries (compressors, ventilators, pumps…)
- Electric household appliances: robots, washing machines, vacuum cleaners…
- Electric traction and aeronautics

In general, the SRG have enough attractive performances to be able to compete with the conventional machines. The SRG is a doubly salient machine. It does not contain any magnets or brushes, and the phases are completely independent. The rotor is made of laminated iron and it does not have any winding. This makes the SRG also mechanically suitable for high-speed applications [2].

Unfortunately, SRG is a multivariable, strong coupling and nonlinear system, it is very difficult to model and analyze. To do so, lots of modeling methods were studied in literature. The circuit simulation program 'SPICE', it has certain limitations [3]. Reference [4] uses object oriented program technique, it is very flexible, but it is difficult to actualize, because it needs the complete mathematical model of the system. Reference [5] introduces some modules and M-file in MATLAB to build the nonlinear mathematical model of the magnetization curves, it is accurate, but the simulation speed is slow.

In this study, we propose a nonlinear modeling method based on circuit simulation built by self-defining M-functions and basic modules on Simulink library. This model is very flexible and visual, its simulation speed is very fast [6].

The control of the switched reluctance machines (SRM) is more complicated for generator operation than it is for motor. In generator mode, the turn-on and turn-off angles control the peak phase currently jointly and severally.

In this simulation model, the power inverter, excitation source, inductor model, design of each phase model, and loads are simulated using Simulink/Sim power system. The turn-on and turn-off angles are the two parameters through which we can control the simulation results really report the work status of the generator system and validate the applicability of the model and the proposed controller.

2. MACHINE DESIGN

In order to keep a good balance between robustness and total power device cost, the machine topology that is chosen in this paper is a 6 poles in stator and 4 poles in rotor. This topology can provide 2/3's of the rated power in case one of the phase fails.

Another factor that needs to be considered for high-speed applications is the core losses, which are proportional to the square of the number of strokes per revolution. The 6/4 SRG has 12 strokes per revolution, which is half the number of strokes of the 8/6 (four phase) SRG. Therefore, the 6/4 (3 phase) machine was chosen.

3. OPERATING PRINCIPLE OF SRG

SRG system is composed by switched reluctance machine, power inverter, and position sensor and so on. In this paper, the subject investigated is three- phase 6/4 pole SRG. The topology of its power converter is three-phase asymmetric half bridge. The rotor of SRG is driven by a prime motor. The position of the motor can be obtained by a position sensor.

The controller can create certain control signals according to the position information of the rotor. The controls signal can drive the switches in power converter to implement excitation and electrical power generation. Fig. 1 shows the SRG diagram and associated converter. When both K_1 and K_2 are turned on the winding is excited; the system absorbs energy from the prime motor and exciting source .When both K_1 and K_2 are turned off, the winding release energy through D_1 and D_2, the system offers electric energy to externals loads.

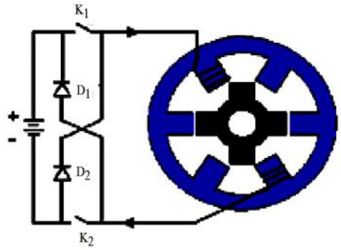

Fig. 1: SRG diagram and associated converter

3.1 Basic equations of SRG

The dynamic mathematical model of SRG includes two basic nonlinear equations, such as electromagnetic equation and flux linkage equation, which are respectively as:

$$\pm V_k = R \times i_k + \frac{d\Psi(\theta, i_k)}{dt} \tag{1}$$

Where V_k is terminal voltage of the winding, i_k is phase current k (k = a, b, c), R is phase resistance, $\psi(\theta, i_k)$ is phase flux linkage, θ is position angle of the rotor.

The sign before V_k is determined by the operating mode of the system. When the system is excited, the sign is plus, when the system is working as a generator, the sign is minus.

Because of the double salient structure of the machine and the magnetic saturation effect, the flux in the stator phases varies according to the rotor position θ and the current of each phase.

$$\psi(\theta, i_k) = L_k(\theta, i_{i_k}) \times i_k \tag{2}$$

$L_k(\theta, i_{i_k})$ is phase inductance, it's depending to the phase current and the rotor position.

3.2 Nonlinear model of inductance

In this paper to study the characteristics of SRG accurately, according to the nonlinear inductance model, a nonlinear SRG model is built based on the electromagnetic field finite-element analysis.

To simulate the dynamic performance accurately, the relational expression of inductance position angular of rotor and phase current must be described exactly. The magnetic circuit of the SRG is saturated and non-linear.

The harmonic component of the inductance can be expressed.

$$L_k(\theta, i_{i_k}) = L_0(i) + L_1(i) \times \cos(N_r \times \theta + \pi) \tag{3}$$

$$L_0(i) = \frac{L_{max}(i) + L_{min}(i)}{2} \tag{4}$$

$$L_1(i) = \frac{L_{max}(i) - L_{min}(i)}{2} \tag{5}$$

Where L_{max} is aligned position inductance, L_{min} is the unaligned position inductance.

The figure 2 shows the relationship between inductance, turn angle of rotor and phase current.

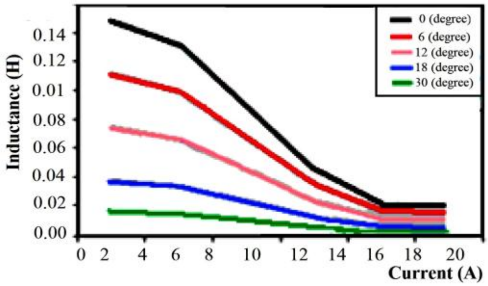

Fig. 2: Relationship between inductance, turn angle of rotor and phase current

L_{max}, L_{min} can be obtained by experiments and electromagnetic field finite element analyzes (FEA).

$L_{max}(i)$ can be expressed as a polynomial function with respect to the phase current which can be obtained by curve fitting, (Fig. 3).

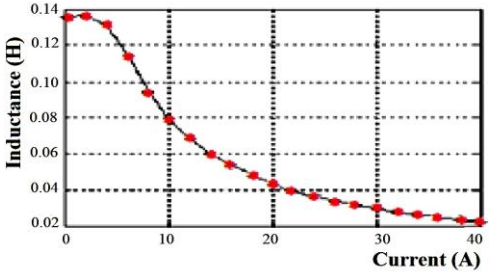

Fig. 3: Fitting curve of $L_{max}(i)$

$$L_{max}(i) = \sum_{n=0}^{4} a_n \times i^n = 0.136 - 0.0045 \times i + 0.0056 \times i^2 - 0.022 \times i^3 + 0.00035 \times i^4 \quad (6)$$

3.3 Torque production

The variation of the reluctance between two extreme positions of aligned and unaligned positions will induce a variation of magnetic energy from which a non null average torque will result.

$$T_e = \frac{1}{2}\frac{dL(\theta,i)}{d\theta} \times i^2 \quad (7)$$

The production of the torque does not depend on the sign of current but only on the sign of $dL/d\theta$. Since the SRG torque is independent of the polarity of exciting current, the SRG requires only one switch per phase winding, contrary to what occurs in the majority of the AC motors where at least two switches per phase are required.

4. SRG POWER CONVERTER

The most commonly used Switched Reluctance Generator is the classical half-bridge converter which has two power switches and two diodes per phase. The figure 4 shows the structure of three-phase power inverter, the main advantage of this inverter is that each phase can be controlled independently.

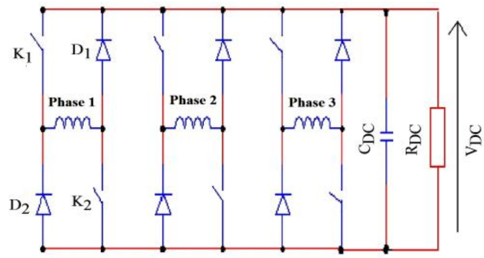

Fig. 4: Power Inverter system of three-phase SRG

4.1 Excitation mode

During this mode, K_1 and K_2 are on to yield the equivalent circuit.

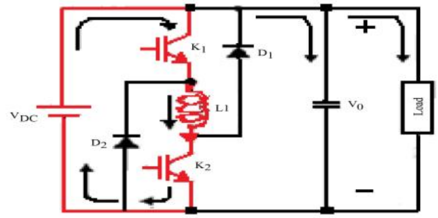

Fig. 4.a: Excitation mode

4.2 Free wheeling current-boosting mode

Initially, the voltage drops of R and L can lead to the decrease in winding current. The current is continuously built up by the negative value of back EMF. During higher speed and higher DC-link voltage, the duration of this mode will be increased.

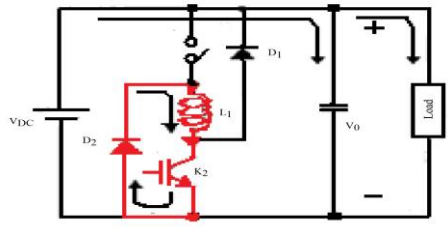

Fig. 4.b: Freewheeling mode

4.3 Generating Mode

During the generating mode, both of the two switches are turned off with the circuit and current path being show in Fig. 4.c. This action will impose the negative DC-link voltage upon the active stator phase, at this time, the mechanical energy from prime mover is converted to electrical energy. The phase winding voltage equation in this mode can be written as follows:

$$-V_0 = R \times i + L \times \frac{di}{dt} + e, \qquad e < 0 \tag{8}$$

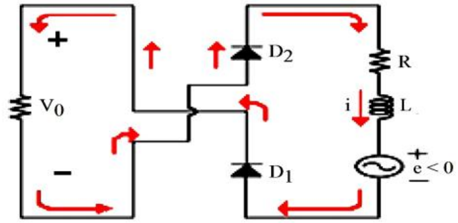

Fig. 4.c: Generating mode

5. SYNOPTIC DIAGRAM

The synoptic diagram of the single-phase control circuit allowing the achieving of the previous goal is shown in figure 5.

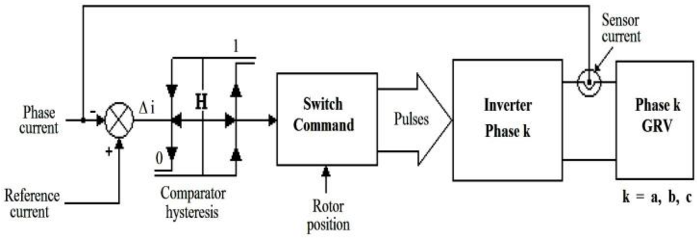

Fig. 5: synoptic diagram of the proposed single phase control circuit

6. NONLINEAR SIMULATION MODEL OF SRG

To make easy the simulation of the SRG the optimal angles of the switches are limited as follows:

$$45° \leq \theta_{on} < \theta_{off} \leq 90°$$

In order to simplify the simulation process, in this paper four assumptions are introduced as follows:

- Parameters of each phase in SRG are symmetrical.
- Ignore mutual inductance and leak inductance.
- Ignore hysteric's and eddy effect.
- Switches in power converter are ideal device and the exciting source is constant.

6.1 Model of each phase

We presents the model of windings, it is built according to (1) - (7). The parameters of each phase are symmetrical, take phase (a) example, its simulation model shows the detailed structure of the nonlinear machine modeling is created by Embedded Block in figure 7.

The two other phases are identical but different just on the level from the value of the angular shift where we take 0° for the phase (a), θ_s for the phase (b), and $2\theta_s$ for the phase (c), θ_s is defined as:

$$\theta_s = 2\prod(1/N - 1/N_s) \tag{9}$$

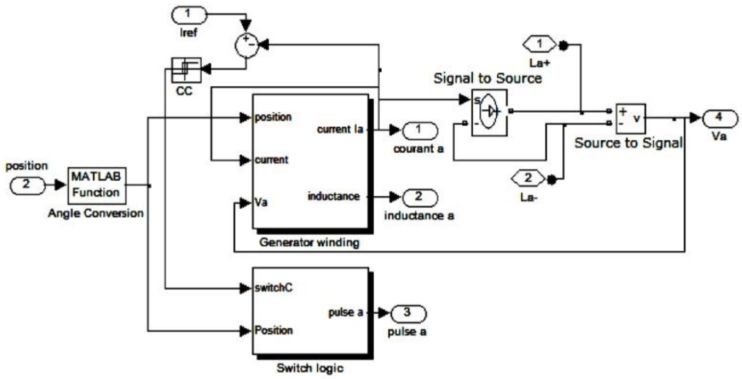

Fig. 6: The simulation model of phase (a)

Signal to Source and Source to Signal are connecting elements between simulink modules and PSB modules. Signal to Source is a controlled current source, it converts current signal to a current source. The figure 8 shows the Inductance and current calculator of the winding.

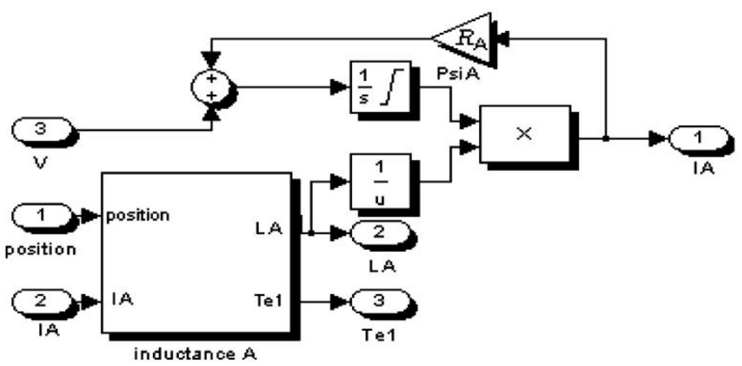

Fig. 7: Inductance and current calculator

In this block, we can also calculate the inductance and the torque of a one phase by applying the formulas (3) to (7), with $L_{min} = 0.01$ H .

6.2 Design of the controllers

The objective of the controller system is to create a high performance control commands to maintain the output voltage of the system. The performance controller seriously affects the dynamic and static characteristics of the system. For SRG, there are many controllable parameters. Turn-off angle θ_{off}, turn on angle θ_{on}, turn-off peak current I_c, and so on.

As a result, there are many typical control strategies. Angle position Control, Current Controller….

Because the performance of system is very sensitive to the turn-off angle, the implement of Angle position Control has certain difficulties. In this paper, a high-performance control strategies named PI+CC control (PCC) is used. The controller has two closed loops: outer voltage closed-loop (VC) and inner current closed-loop (CC).

VC θ_s shown in figure 8 is based on PI controller. Firstly it obtains the D-value between the output voltage of the system and the given voltage signal (270 V), and then creates the reference current I_{ref} through PI controller.

CC is based on current chopping control; it is implemented by the Relay module in Simulink library as shown in figure 6. By the way, turn-on and turn-off angle in this controller is optimized and fixed.

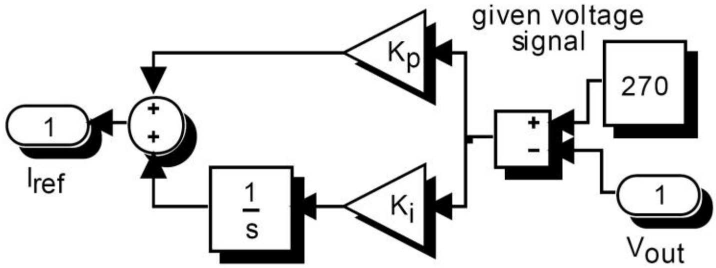

Fig. 8: Simulation model of outer voltage controller

6.3 Model of prime mover

The turbine model used in this study as a prime mover is shown in Figure 9.

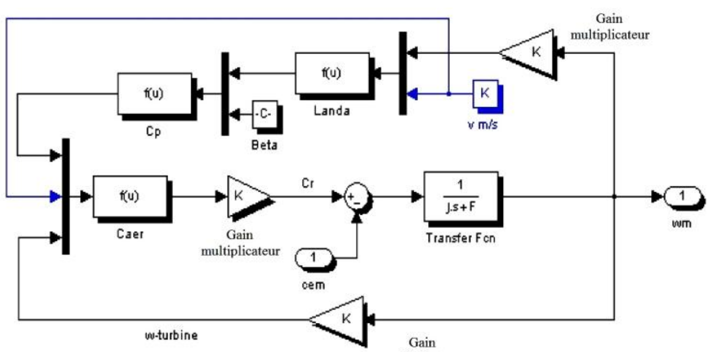

Fig. 9: Model of the turbine

6.4 Exciting circuit and loads

The direct current exciting source V_{DC} supplies the original exciting current to the windings. The Diode module over V_{DC} is used to prevent the current of SRG from returning to V_{DC}.

The switching device over load it use to imitate sudden load-on and load-off, it is composed of an IGBT module and a step-function signal module.

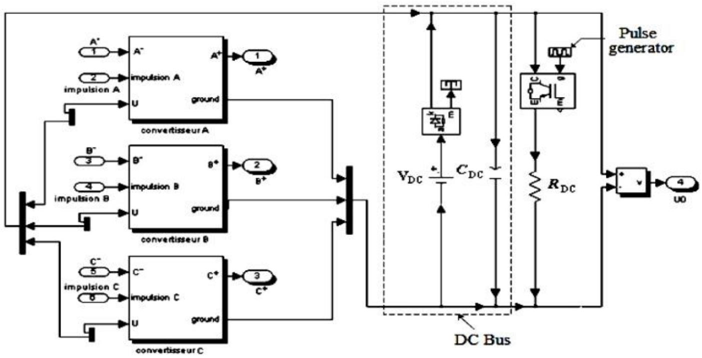

Fig. 10: PSB simulation model of exciting source and loads

To test the proposed model feasibility a three phase 6/4 SRG system is built and simulated as shown in figure 11. The rated parameters of the SRG are 3000 r.p.m, 250 volt. The SRG was simulated under different conditions.

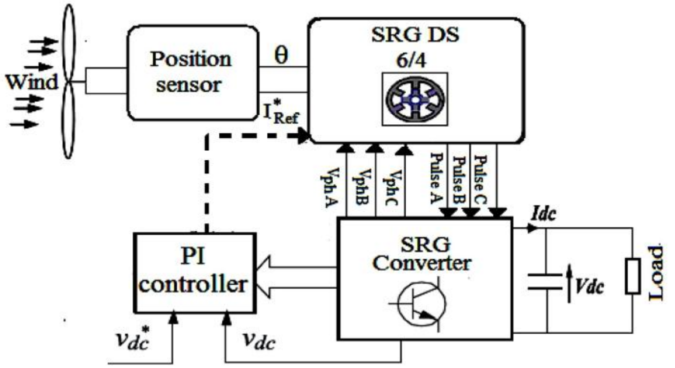

Fig. 11: Simulation model of SRG system

7. NONLINEAR SIMULATION RESULTS

The figure 12 shows the nonlinear inductance phase and its variation when the rotor position changed.

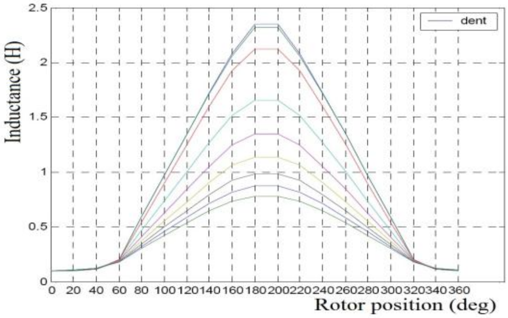

Fig. 12: Inductance waveforms

7.1 Current controller

In current controller CC, both power switches are turned off when windings current reaches threshold in ascending inductance region. Windings current will not exceed current command I_c by chopping. The phase current is uncontrollable in the region of generating. Current waveforms versus chopping command are shown as Fig. 13.

When the system is working in the generating region, the back EMF may make the phase current increase above I_c , in spite of both power switches are turned off. The current is limited by chopping control during decreasing region of inductance. However, it may still increase during the decreasing region of inductance, which leads to that the area of current during the decreasing region of inductance is bigger than that during increasing region of inductance.

7.2 PI controller with CC

The PI controller with CC has more controllable parameters comparing to the two typical controllers above: k_p and k_p as shown in figure 8. It is very flexible to be adjusted.

The voltage will stabilize after a short time. The ripples of the voltage are very small. The figures 14 present the current waveform of three phases.

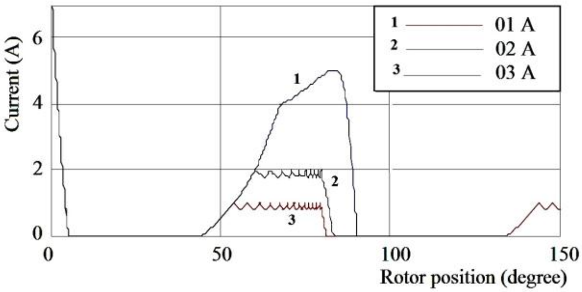

Fig. 13: Simulation waveforms of phase current with CCC (θ_{on} =45°, θ_{off} =80°, speed=3000 rpm).

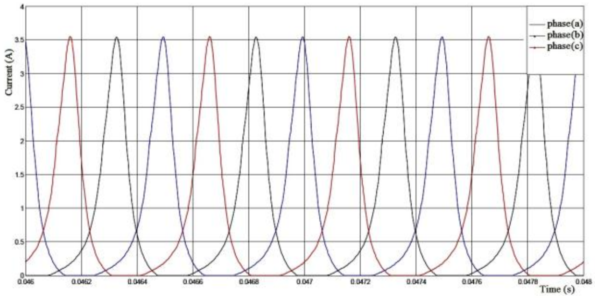

Fig. 14: Phase current (a)

The figure 15 indicates the circle where the controllable switches are turned off.

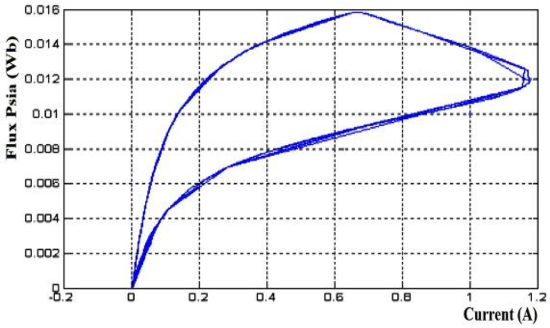

Fig. 15: Energy conversion cycles for the SRG of Fig. 1(speed=5000 rpm)

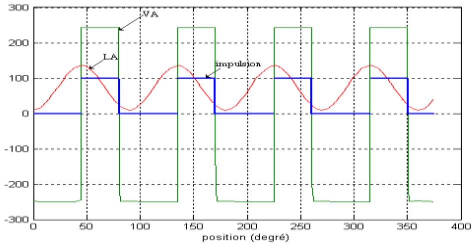

Fig. 16: Influence of the pulses on the voltage and the inductance of the machine

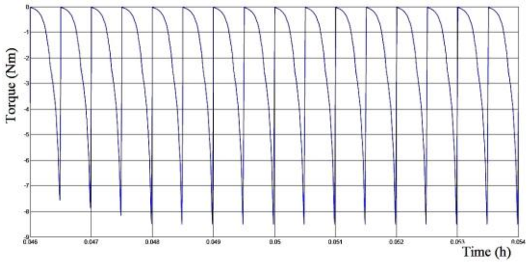

Fig. 17: Waveform of the torque (Nm)

8. CONCLUSIONS

Switched reluctance generator has been investigated as a feasible candidate for wind power applications and found to be a better one as it lacks starting torque [7]. The research on SRG in wind energy application is still ongoing and further research on the machine is required before it can be widely used.

There are many nonlinear characteristics in the SRG system. When the operation conditions and loads are changed, the characteristics of some components in SRG system will be changed. So it is difficult and complex to build the model by a simply use of a mathematical model and nonlinear inductance model, this paper built a complete nonlinear simulation model of SRG system based on Matlab/Simulink.

This proposed SRG minimized the ripple, and constant steady state output voltage is stabilized. The simulation results really report the work status of the generator system, validate the applicability of the model.. The obtained results in this paper show that the simulation model provides an efficient SRG that is easy to implement.

APPENDIX

Values of parameters used in modeling and simulation

$$R = 25\Omega,\ N_r = 4,\ L_{min} = 0.01H,\ V_{exciting} = 250V,$$

$$R_L = 100\Omega,\ \theta_{original} = 10°,\ K_p = 10,\ K_i = 5$$

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