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OPTIMAL DESIGN AND CONTROL OF AC-DC-DC WIND ENERGY SYSTEM FOR ELECTRIC VEHICLE BATTERIES RECHARGING STATIONS

Saber Hadj Abdallah* and Souhir Tounsi**

Abstract

This paper presents an optimal design and control methodology of wind energy system based on AC-DC-DC power conversion regulating conjointly turbine speed and battery load voltage to permit energy recovery in a battery accumulator at optimal regime. This application is dedicated to electric vehicles battery charging stations. The wind energy system allows a speed regulation permitting to avoid the use of an electromechanical braking system during over-speed phases accompanied by dangerous over-currents in the goal to reduce the cost of the wind power system. Indeed, the developed control technology allows a speed regulation of the electric generator to its optimal value, to avoid any over-speed problems leading to strong increases in current in the electrical components of the wind turbine, and subsequently to its destruction. This control technology also makes it possible to maintain the induced electromotive forces in phase with the phase's currents of the generator to have an additive electromagnetic torque to the useful torque of the turbine in the goal to optimize the recovered energy. This control technology is based on two conversions types, one is an alternative-continuous conversion performed by an AC–DC converter with insolated gate bipolar transistors (IGBTs), and the other is a DC–DC conversion performed by a booster chopper, used to regulate the batteries recharging voltage to its nominal value.

Key Words

Wind energy, speed regulation, AC–DC inverter, DC–DC inverter, optimal control, system cost reduction

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1. Introduction

This paper concerns a wind energy system permitting an AC-DC-DC energy conversion using AC–DC and DC–DC inverters to recharge batteries at optimal regime, used in electric vehicles recharge stations.

The design and control of the wind turbine system is based on a configuration extracted partially from the studies presented in [1]–[5], illustrating various structures of AC-DC-AC wind energy conversion chains. Indeed, the AC-DC-AC conversion chain presented in [1]–[5] are modified, while keeping the same operating principle, by an AC-DC-DC conversion chain to have a conversion chain structure converting the wind energy on electrical energy recoverable on batteries. This study permit the reduction of the production and maintenance costs of wind energy conversion chains, conventionally comprising an electromechanical or hydraulic braking system, for their protection against over-speed problems, leading to over-currents in the electrical components of these chains. Indeed, the wind chains are subject to speed constraints due to the variation and the elevation of the wind speed, leading in general to the use of electromechanical braking systems. These braking systems cause severe vibrations and wear of friction parts, also an important increase of maintenance and production costs of the wind turbines. In this context, several research works deal with this problem. For example, in [6], analytical and experimental torque calculations of permanent axial magnet eddy-current brake are presented for wind braking systems. This study shows clearly the complexity of the studied wind system leading to an increase of its production and maintenance costs. Yazdanpanah and Mirsalim [7] presented the use of braking by eddy-current. These technologies of wind energy systems are recent, but they need a complex control system and are with elevated production and maintenance costs. Deshpane [8] presented a braking method using hydraulic systems. This study is also recent, but it is expensive, and it requires a high maintenance cost of the mechanical components. These mechanical systems also lead to dangerous vibrations which can cause deterioration of mechanical components

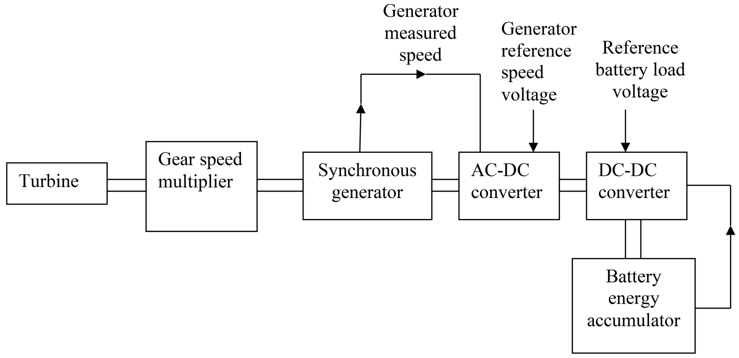

Figure 1. Wind energy generation chain structure.

by bending. A reconfigurable control for fault-tolerant of parallel wind power converters is proposed in [9]. This study uses parallel converters, which makes the power system expensive. This study also does not allow continuous protection in the event of a sudden variation of the wind, and it is not based on a systemic sizing study guaranteeing continuous protection of the components of the power chain.

For this study, the electrical generator is designed by a systemic method combining the analytical and the finite elements methods, taking into account the interactions between the components of the power chain and the operating constraints, such as the sudden variation of the wind [10]–[14]. In addition, this study concerns the regulation of the speed of the turbine at its nominal value by an AC–DC converter controlling the magnitude of the generator phase's currents and imposing the electromotive forces in phase with the phase's currents of the generator to have an electromagnetic torque which is added to the useful torque of the turbine. Another point is taken in account by this study is the adjustment of the battery recharging voltage to its optimal value to recover the maximum amount of energy. The studied system is less expensive compared to the already existing systems, since the energy conversion only requires an AC–DC converter and a booster chopper.

In this context, this paper is organised as follows:

- Description of the control strategy.
- Modelling of the wind turbine under MATLAB-Simulink simulation environment.
- Description of simulation results.
- Conclusions and perspectives.

2. Control Strategy

The power chain is illustrated in Fig. 1. A speed proportional-integral-derivative regulator is used to maintain the speed of the permanent magnet generator continuously equal to its optimal value regardless of the wind speed cycle. Indeed, the reference speed of the generator is compared to the measured speed. The comparator output is the input of a proportional-integral-derivative regulator to provide the amplitude of the generator reference currents. The shapes of the currents are imposed the same as the induced electromotive forces,

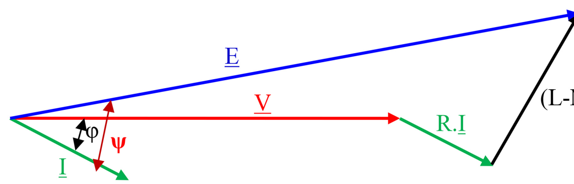

Figure 2. Vector diagram of synchronous generator.

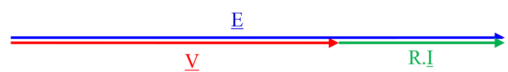

Figure 3. The equivalent vector diagram.

and in this way the electromagnetic torque will be an additive torque to the useful torque of the wind turbine. This regulation technique allows optimal energy recovery at the battery energy accumulator. The generation of the six control signals of the AC–DC inverter is ensured by pulse width modulation (PWM) of the three reference currents by comparisons to a triangular signal. The outputs of the three comparators attack three hysteresis varying between logical '1' and '0', knowing that for the same arm the two control signals of the two insolated gate bipolar transistors (IGBTs) are complementary. To ensure optimum recharging of the battery energy accumulator, a booster chopper is used to generate the optimum recharging voltage of the batteries. In fact, a proportional-integral-derivative regulator is used to generate the reference voltage for recharging the battery energy accumulator. The batteries recharging reference voltage is compared to the recharging voltage delivered by the booster chopper. The output of the comparator is the input of a proportional-integral-derivative regulator generating the reference voltage which pulses at the rate of the control signal of the booster chopper obtained by PWM of this voltage by the intermediary of a triangular signal and an hysteresis varying between '0' and '1' logic.

In conclusion, the wind energy system operates at its optimal regime with protection against over-peed accompanied by over-current in the electrical components.

The vector diagram of synchronous generator operation mode is shown in Fig. 2.

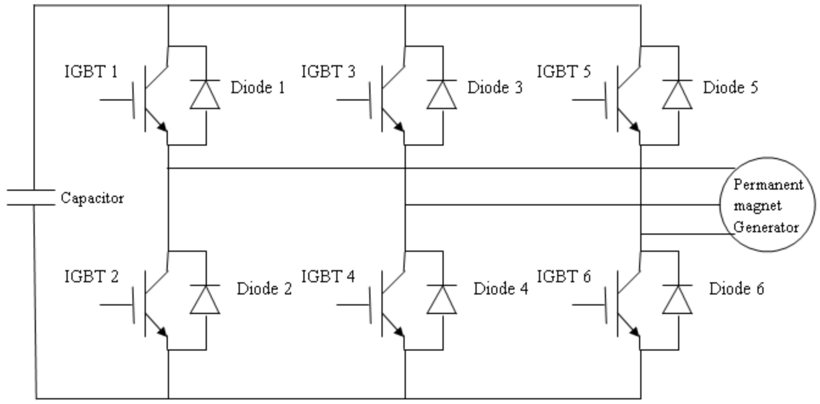

Figure 4. AC–DC converter structure.

Where V is the phase's voltage vector, E is the induce electromotive force vector, I is the phase's current vector, L is the phase's inductance, M is the phase's mutual inductance, Ω is the generator angular speed, and p is the number of poles pairs.

For a neglected equivalent generator phase's inductance and a control of the AC–DC inverter maintaining stator phase's currents in phase with induced electromotive forces, the equivalent vector diagram becomes as shown in Fig. 3. In this case, the angle ψ is equal to zero and the turbine is at the optimal functioning regime.

The capacitance used as the receiver of the AC–DC converter is intended to smooth the output voltage of this converter.

The structure of the AC–DC converter is illustrated in Fig. 4.

3. Modelling of the Wind Energy Generation Chain Components

3.1 Induced Electromotive Forces

The three induced electromotive forces e_a, e_b, and e_c are expressed by the following three equations [10]–[15]:

$$e_a = \frac{2}{3} \times K_e \times \Omega \times \cos\left(p \times \Omega \times t + \frac{\pi}{2}\right) \quad (1)$$

$$e_b = \frac{2}{3} \times K_e \times \Omega \times \cos\left(p \times \Omega \times t + \frac{\pi}{2} - \frac{2 \times \pi}{3}\right) \quad (2)$$

$$e_c = \frac{2}{3} \times K_e \times \Omega \times \cos\left(p \times \Omega \times t + \frac{\pi}{2} - \frac{4 \times \pi}{3}\right) \quad (3)$$

where K_e is the electric constant of the generator, Ω is the generator's angular speed, and p is the pole pairs number.

3.2 Control Signals Generator

The control signal generator compares the three reference voltages to a triangular signal having a frequency much greater than the voltages provided by the regulators of currents. The output of each comparator drives a hysteresis variant between '0' and '1' logic to reproduce the suggested form of the control signals of the IGBTs transistors.

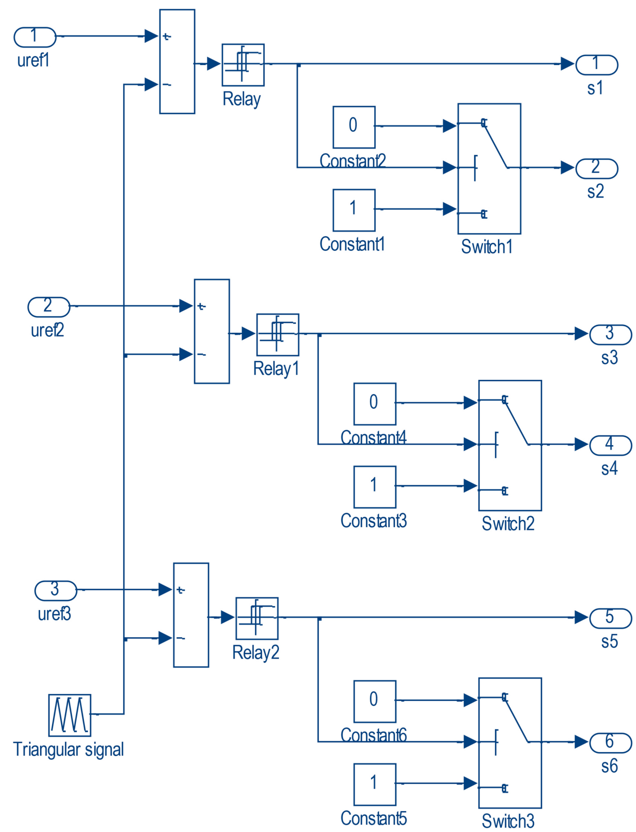

Figure 5. Model of the control signal generator.

The Simulink model of the control signals generator is illustrated in Fig. 5.

3.3 Model of Generator–Converter Assembly

Each generator's phase is equivalent to a resistor in series with the phase's equivalent inductance and the induced electromotive force. The generator three phase's model is described by the following equations [10]–[15]:

$$e_a = v_a + R \times i_a + (L - M) \times \frac{di_a}{\mathrm{dt}} \quad (4)$$

$$e_b = v_b + R \times i_b + (L - M) \times \frac{di_b}{\mathrm{dt}} \quad (5)$$

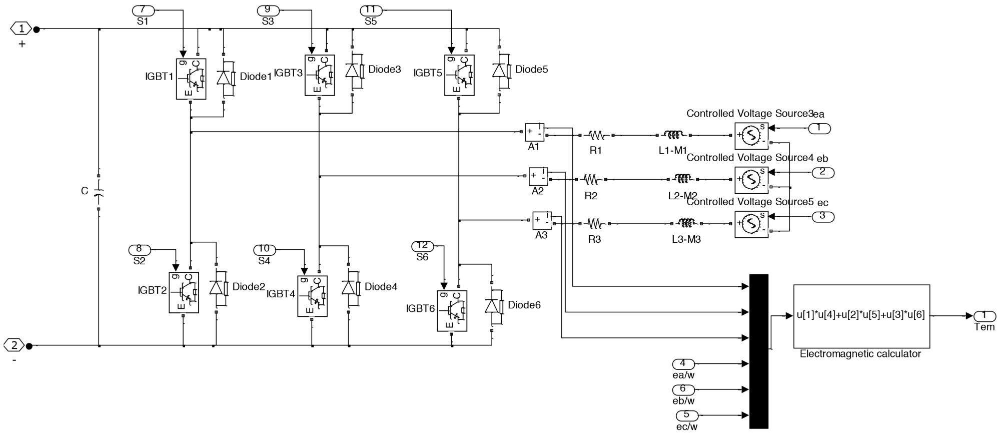

Figure 6. Model of the generator–converter.

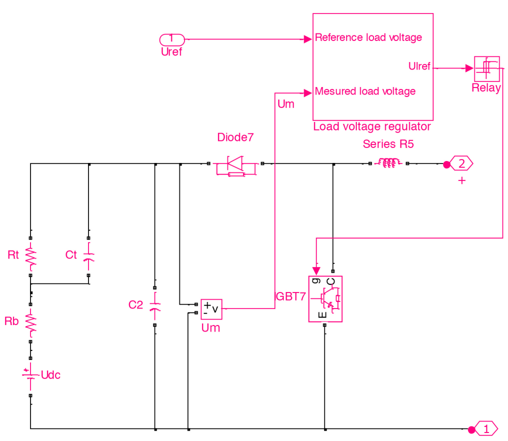

Figure 7. DC–DC inverter regulating battery load voltage by pulse width modulation.

$$e_c = v_c + R \times i_c + (L - M) \times \frac{di_c}{\mathrm{d}t} \qquad (6)$$

where R, L, and M are, respectively, the resistance, the phase's equivalent inductance, and the mutual inductance of the phases a, b, and c, $i_{a,b,c}$, $e_{a,b,c}$, and $v_{a,b,c}$ are, respectively, the currents, the induced electromotive forces, and the voltages of the phase a, b, and c.

The model of the generator–converter-battery assembly is implanted under MATLAB-Simulink according to Fig. 6.

3.4 DC–DC Inverter Pulse Width Modulation Control

The use of a DC–DC inverter (Fig. 7) is in the goal to regulate the charging voltage of the battery. Indeed, the reference charging voltage is compared to the measured response voltage. The output of the comparator attacks a proportional-derivative-integral regulator to generate the ideal reference voltage regulating the charging current at its desired value. In addition, the reference voltage is modulated by a triangular signal and a hysteresis variant between logical '0' and '1'. The value of the inverter inductance is adjusted iteratively to reduce the charging voltage fluctuations. The switching frequency is reduced to 100 Hz to reduce the electromagnetic interference and noise.

3.5 Generation Chain Global Model

The global model of the power chain is implanted under MATLAB-Simulink environment as given in Fig. 8.

4. Simulation Results and Discussion

4.1 Rated Functioning Regime of the Turbine

Simulations of the power chain model are realised according the data extracted from wind turbine analytical model as shown in Table 1.

The battery rated optimal angular speed is the speed related to electric currents maximal values used for wind energy system design model.

Figure 9 illustrates the wind speed cycle. Figure 9 shows that the wind speed cycle includes zones of wind over-speed and wind abrupt change of speed. This speed cycle is used to analyse the behaviour of the wind turbine for critical operating points, allowing to increasing the performance of the wind turbine in the case of operation with natural climatic conditions.

The evolution over time of the rotational angular speeds of the generator is given by Fig. 10. Figure 10 illustrates that the angular speed of the generator is regulated at its nominal value relating to optimal functioning regime by acting on the electromagnetic torque depending on the regulated phase's currents. This regulation is used to set the magnitude of the induced electromotive forces in its optimal value.

Figure 11 illustrates the evolutions of the generator phase's voltage according induced electromotive forces in versus time. Figure 11 demonstrates that the phase's voltages v_a, v_b, and v_c are in phase, respectively, with the phase's induced electromotive forces e_a, e_b, and e_c, due firstly to the reduced value of the generator phase's equivalent inductance and secondly to the regulation of the shift between the phase's currents and the induced electromotive forces at zero.

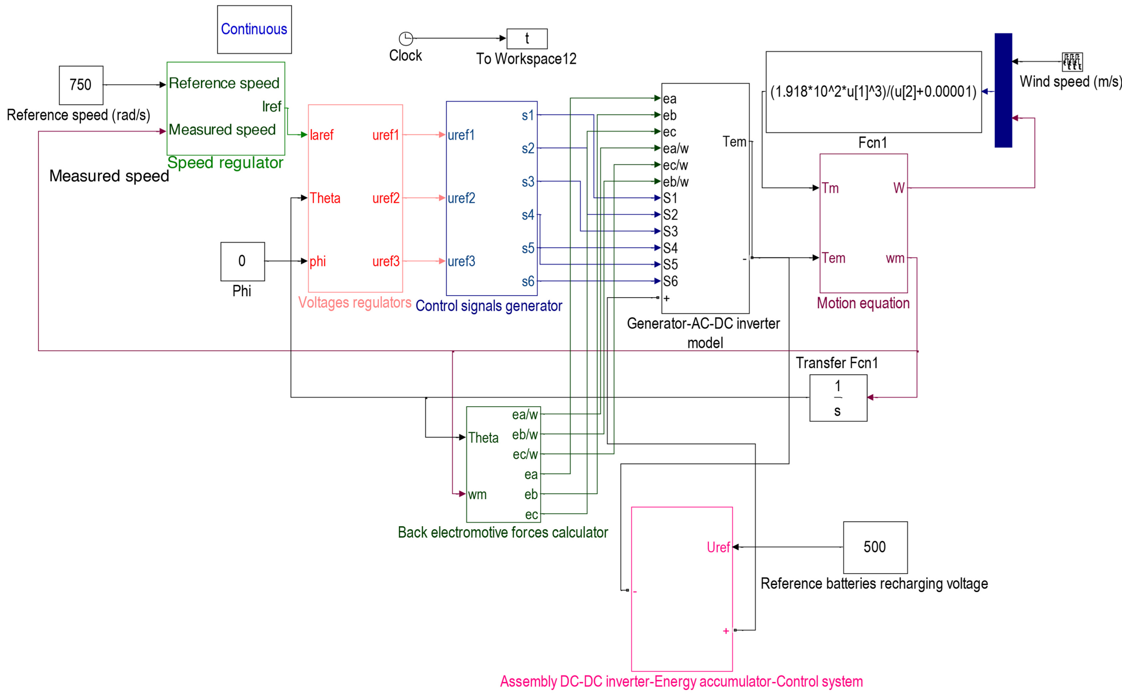

Figure 8. Global model of the wind energy generation chain.

Table 1
Simulation Parameters

Parameters	Values	Units
Battery nominal voltage (U_{dc})	$\sqrt{2} \times 220$	Volts
Internal resistance of the battery (R_b).	0.4	Ω
Transient regime battery resistance (R_t).	0.2	Ω
Generator's electric constant (K_e).	0.4	Volt/(rad/s)
Generator phase's resistance (R).	0.0115	Ω
Generator phase's inductance (L).	0.00676579136	mH
Generator phase's mutual inductance (M).	0.00440625320	mH
Switching frequency (f_{sw}).	100	Hz
Gear ratio (r_d).	100	/
Battery rated optimal angular speed (Ω_m).	400	rad/s
Battery rated optimal charging voltage (U_b).	850	Volts
Battery rated optimal charging current (I_b).	900	A

Figure 12 illustrates the paces of the generator phase's induced electromotive force and current of the phase 'a' in versus time. Figure 12 illustrates that the generator phase's induced electromotive forces are in phase with the phase's currents. This property validates the control law imposing the phase's currents in phase with the electromotive forces to have an electromagnetic torque which is added to the useful torque of the turbine after amplification by the gear train.

Figure 13 illustrates the evolution of battery charging voltage. Figure 13 shows that the response charging voltage follows with good precision the reference charging voltage, which validates the performance of the developed control technique. Figure 13 shows also that the battery charging current varies relatively to the variation of the battery charging voltage. This property is justified by the use of batteries Thevenin model. Figure 13 shows also a low effect of the commuted current in booster chopper inverter's inductance in the form of the battery charging current, which is justified by the correct method of calculating the booster chopper inductance.

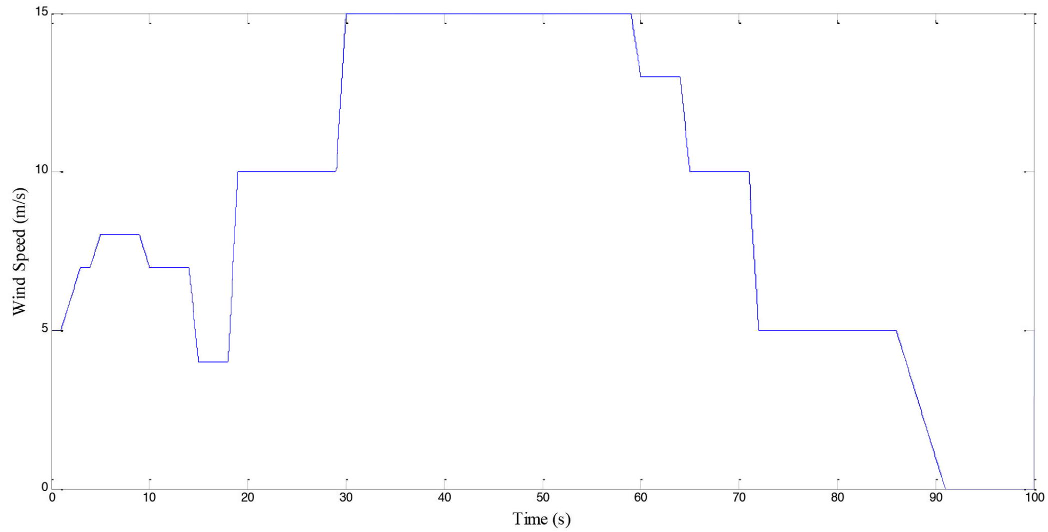

Figure 9. Wind speed variation in versus time.

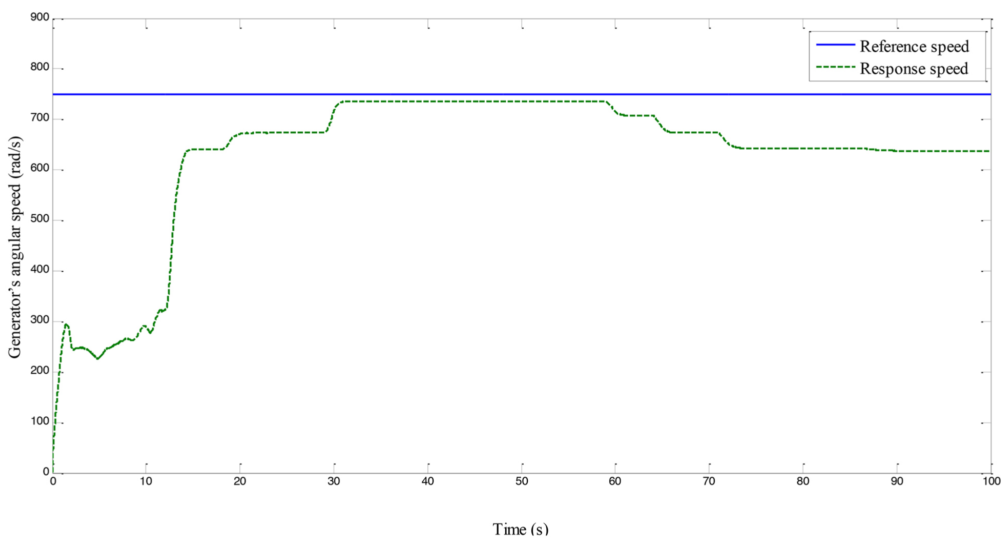

Figure 10. Evolution of the rotational angular speed of the generator.

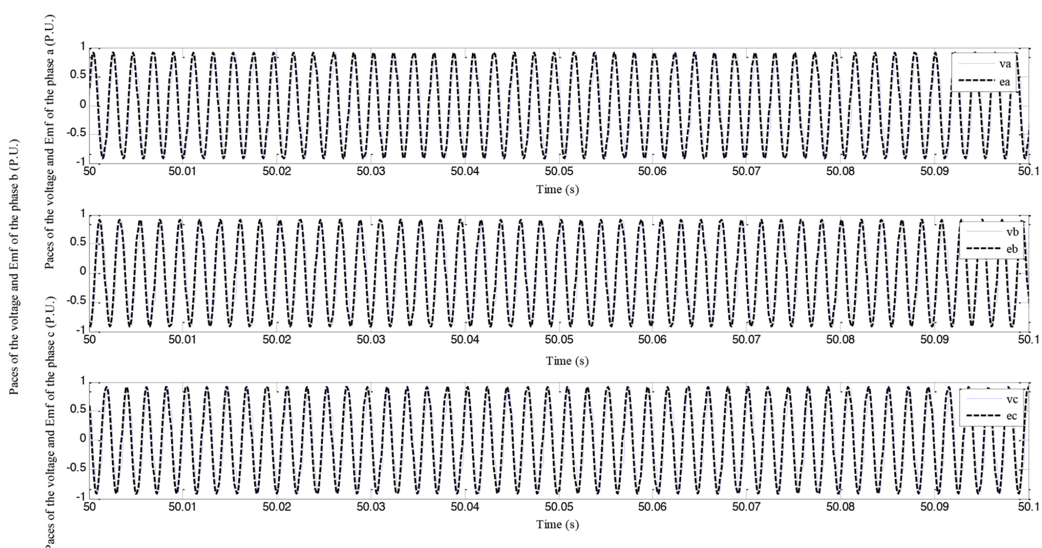

Figure 11. Zoom of the evolutions of the generator phase's voltages according induced electromotive forces in versus time.

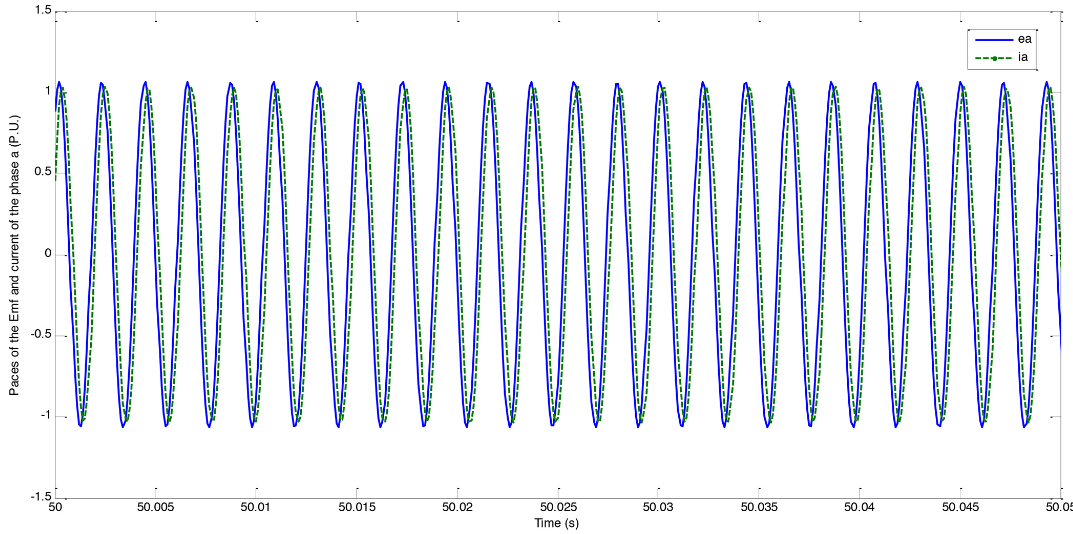

Figure 12. Paces of the generator phase's induced electromotive force and current of the phase 'a' in versus time.

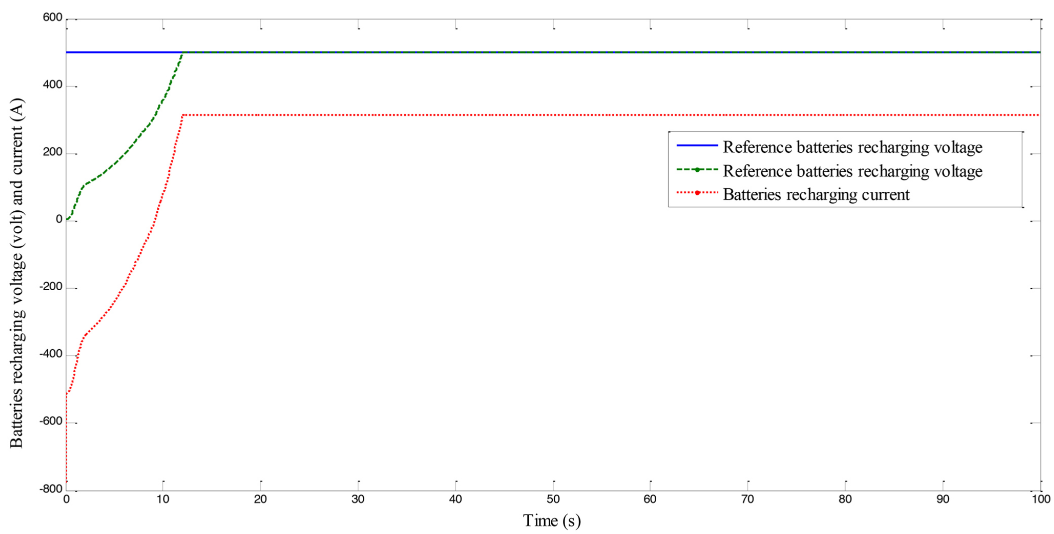

Figure 13. Evolution of battery charging voltage and current.

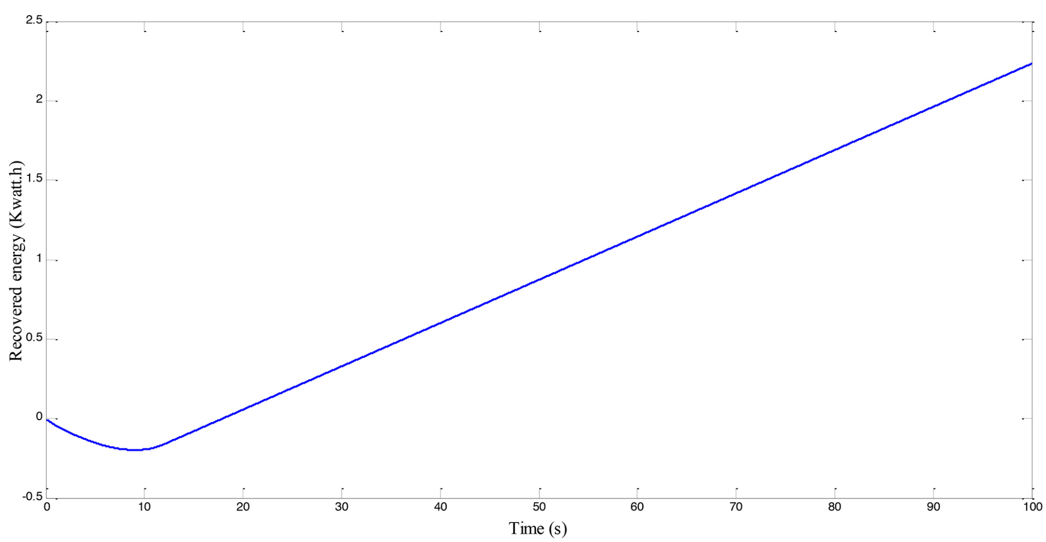

Figure 14. Evolution of the recovered energy.

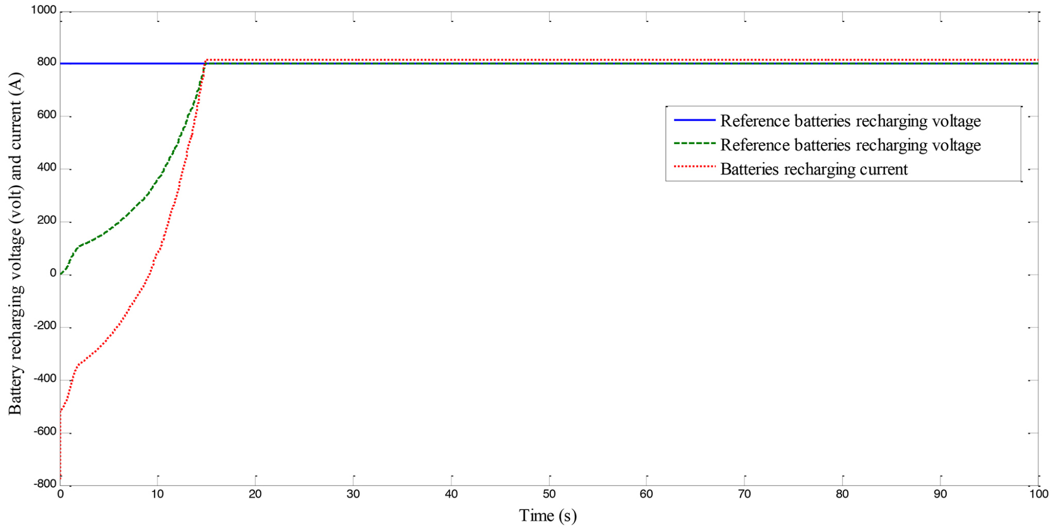

Figure 15. Optimised battery recharging voltage and current in versus time.

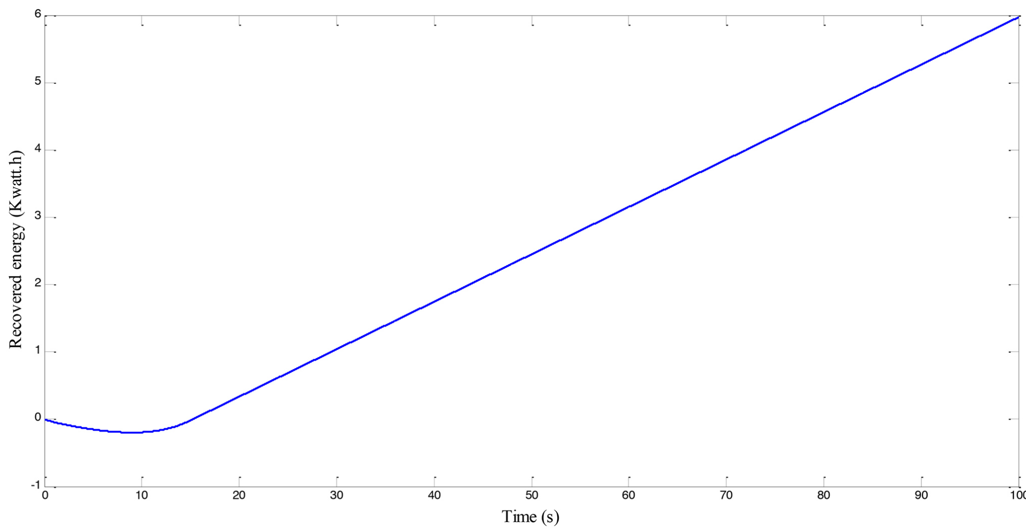

Figure 16. Optimised recovered energy in versus time.

Figure 14 illustrates the important value of the recovered energy due to the elevated charging current of the battery.

4.2 Optimal Functioning Regime of the Turbine

To extract the maximum of energy, wind turbine power system can be sized for the same nominal angular speed of the generator and for an elevated battery charging current by regulating the battery charging voltage to 800 V. The nominal internal battery voltage can be maintained constant in this case, and the sizes of the wind turbine components can be determined systemically from inverse analytical program of the turbine having as inputs the maximal current in the battery. This method is used for sizing electric vehicles to shown in [1]–[4].

For a maximal charging current of battery equal to 930 A, illustrated in Fig. 15, battery load voltage is regulated to 800 V by DC–DC inverter as shown also in Fig. 15.

Figure 16 illustrates that the battery recovered energy is augmented largely regarding the first wind turbine. In conclusion, the efficiency of the wind turbine is largely improved.

The simulations results are validated by the use of two solvers to know:

- Fixed step ode 1 (Euler) with step equal to 0.0001 s.
- Fixed step ode 4 (Runge-Kutta) with step equal to 0.0001 s.

5. Conclusion

This paper presents a new control technique for wind turbines recovered energy optimisation. This technology makes it possible to convert the kinetic energy of the wind into energy recoverable by battery used as an energy storage accumulator. This control technology is based on the first hand on the regulation of the electric generator's angular speed at its optimal value, to protect the power chain against over-current caused by wind over-speed, and on the other hand on the regulation of the battery charging current to its optimal value to optimise the battery recovered energy. In addition, the developed control technology makes it possible to impose the electromotive forces in phase with the phase's currents, to maximise the induced electromotive forces magnitude, and then maximise the recovered energy. This control technique allows a continuous recharge with maximal batteries charging current and voltage. The developed model is implemented under MATLAB-Simulink simulation environment. The analysis of simulation results validates and shows the performances of the developed control technique. The presented study can be validated using Xilinx simulator.As prospects, it will be interesting to industrialise the innovated wind energy system.

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Biographies

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