Nghiên cứu chế độ làm việc của máy phát điện cảm ứng kích từ kép khi có ngắn mạch trên lưới gần nhà máy điện gió

Trần Dương Hoàng Phúc, Lê Thái Hiệp*

Khoa Kỹ thuật và Công nghệ, Trường Đại học Quy Nhơn, Việt Nam

Ngày nhận bài: 24/11/2020; Ngày nhận đăng: 25/12/2020

TÓM TẮT

Bài báo này nghiên cứu về chế độ làm việc của máy phát điện gió loại máy phát điện cảm ứng kích từ kép (DFIG) để đánh giá khả năng vượt qua sự cố thoáng qua trên lưới điện gần nhà máy. Dựa trên cấu tạo của máy phát điện loại DFIG, việc sử dụng điện trở nối trực tiếp với dây quấn rôto sẽ đưa máy phát hoạt động như một máy phát điện không đồng bộ rôto dây quấn (WRIG) khi có ngắn mạch trên lưới. Theo kết quả mô phỏng trên Matlab thì, khi đó công suất tác dụng được tiêu thụ trên điện trở phụ crowbar làm cho đặc công suất phát chuyển đổi từ cao sang thấp. Nhờ đó lượng công suất cơ dư thừa không nhiều, cho nên máy phát không bị tăng tốc đáng kể. Kết quả mô phỏng này cho thấy việc sử dụng điện trở phụ crowbar để thay đổi đặc tính công suất của DFIG là phù hợp. Chính nhờ cách chuyển đổi này giúp máy phát vẫn kết nối với lưới, vận hành ổn định cả trong và sau sự cố ngắn mạch.

Từ khóa: *Máy phát điện gió, máy phát điện cảm ứng kích từ kép (DFIG), máy phát điện không đồng bộ rôto dây quấn (WRIG), ngắn mạch, crowbar.*

*Tác giả liên hệ chính.
Email: lethaihiep@qnu.edu.vn

JOURNAL OF SCIENCE
QUY NHON UNIVERSITY

Study on operating modes of doubly fed induction generator with a short circuit fault on grid near the wind power plant

Tran Duong Hoang Phuc, Le Thai Hiep*

Faculty of Engineering and Technology, Quy Nhơn University, Viet Nam

Received: 24/11/2020; Accepted: 25/12/2020

ABSTRACT

In this paper, the operating mode of a doubly fed induction generator (DFIG) wind turbine is studied in order to evaluate its fault ride-through and transient stability with a grid's short circuit fault at near the wind power plant. Based on the structure of DFIG, external resistors are directly connected to rotor windings, then the generator operates as a wound rotor induction generator (WRIG) when there is a short circuit fault on the grid. According to the simulation results in Matlab, the active power is consumed on the crowbar resistor, causing the active power characteristic of generator changing from high to low. As a result, the amount of excess mechanical energy is not much, so the generator is not accelerated significantly. These simulation results show that it is appropriate to use the crowbar resistor to change the power characteristic of the DFIG. Thanks to this change, the generator is still connected to the grid, and operares stably during and after a short circuit.

Keywords: *Wind power generator, doubly fed induction generator (DFIG), wound rotor induction generator (WRIG), short circuit fault, crowbar.*

1. INTRODUCTION

Electricity is mainly generated by hydroelectric and thermal power using fossil fuels. Currently fossil fuels are increasingly depleted resulting in rising the cost of the products using them. To solve this difficulty, one seeks to replace them by other energy sources, such as solar, wind energy. Wind energy is one of the clean energy researched and applied in the field of electricity generation.

However, during operation of wind power plant, it is inevitable that there is a short circuit outside one. At this time, the wind generators are not allowed to disconnect from the grid in order to participate in supporting this grid to ride through the fault. Doubly Fed Induction Generator (DFIGs), which are variable - speed wind generations, are commonly used in the world, and used at all wind power plants in Vietnam. DFIG's properties is not similar to synchronous generators' ones (synchronous generators are used in hydropower, thermal power, diesel power…). Therefore, it is necessary to have a detailed study of the characteristics and operating modes of the wind generator when there is a short circuit outside the wind power plant.

This problem is expected to give some solutions, to help wind power plants operate safely and stability. Many studies have shown that it is necessary to use a crowbar resistance for DFIG when there is a short circuit.[1-4] There have also been researches indicating how to control for DFIG wind generators to ride-through grid

*Corresponding author.
Email: lethaihiep@qnu.edu.vn

faults,[1,3-5] for transient stability improvement in grid.[6] Besides, the effects of crowbar resistor on DFIG's power curve have been analyzed.[1] In Vietnam, there have also been research on voltage instability at grid connected wind power plants.[7] However, there has not yet been a detailed review of the state of the power system to consider whether to improve or deteriorate when DFIGs are connected to it. This paper presents research with the aim of finding the answers to the above problems.

2. THE WIND POWER GENERATOR

2.1. Wind power generator

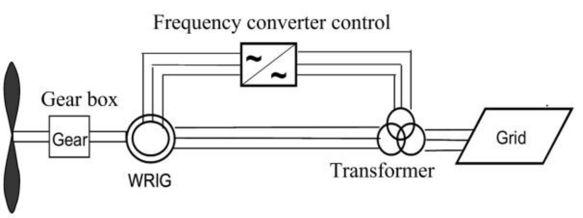


Figure 1. Basic structure of the DFIG wind turbine. [8-10]

Commonly, a DFIG wind turbine is designed on basic structure as shown in Figure 1 and control structure as shown in Figure 2. The generator is an induction machine with a wound rotor, which is connected via a back-to-back converter, while the stator is directly connected to the grid. The rotor-side converter (RSC) is connected to the grid-side converter (GSC) using a DC link.[8]

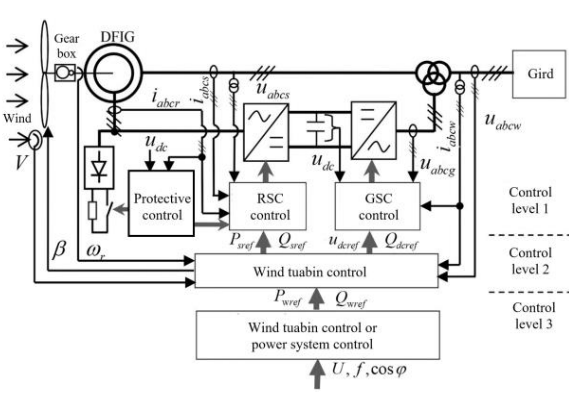


Figure 2. Basic configuration of a DFIG wind turbine connected to a power grid.[11,12]

2.2. Wind power generator model

The equivalent circuit of DFIG is shown in Figure 3.

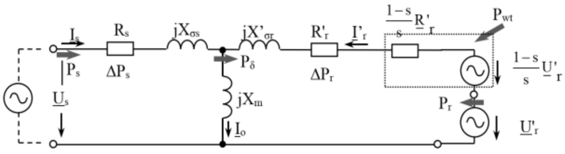


Figure 3. Power flow in the DFIG is illustrated with the equivalent circuit. [9]

From the equivalent circuit, the following voltage equations can be written:

$$\underline{U}_s = R_s \underline{I}_s + jX_{\sigma s} \underline{I}_s + jX_m \underline{I}_0 \quad (1)$$

$$\frac{\underline{U}'_r}{s} = \frac{R'_r}{s} \underline{I}'_r + jX'_{\sigma r} \underline{I}'_r + jX_m \underline{I}_0 \quad (2)$$

With:

U_s – stator voltage

I_s – stator current

U'_r – rotor voltage related to stator side

I'_r – rotor current related to stator side

R_s – stator winding resistance

R'_r – rotor resistance related to stator side

$X_{\sigma s}$ – stator leakage reactance

$X'_{\sigma r}$ – rotor leakage reactance related to stator side

X_m – magnetizing reactance

s – slip

In Figure 3: ΔP_s, ΔP_r – stator winding losses and rotor winding losses; P_s, P_r – stator power and rotor power; P_{wt} – mechanical power, P_δ – air gap power.

Equation (3) shows the power transmitted through the air gap calculated according to the mechanical power received from the turbine.

$$\begin{aligned} -P_\delta &= P_{wt} + 3\Re e\{\underline{U}'_r \underline{I}'^*_r\} - 3R'_r |\underline{I}'_r|^2 \\ &= P_{wt} + P_r - \Delta P_r \end{aligned} \quad (3)$$

With:

$\Re e\,\{\underline{X}\}$ – Real part of complex numbers $\underline{X}$;

$\underline{X}^*$ – complex number with $\underline{X}$;

$|\underline{X}|$ – module of complex number $\underline{X}$.

The air gap power is calculated according to the stator-side parameters:

$$P_\delta = P_s - 3R_s |\underline{I}_s|^2 = P_s - \Delta P_s \quad (4)$$

On the other hand, P_δ can also be represented:

$$P_\delta = 3\frac{R'_r}{s}\left|\underline{I}'_r\right|^2 - 3\Re e\left\{\frac{\underline{U}'_r}{s}\underline{I}'^*_r\right\} \qquad (5)$$

From the above equations we can write:

$$s.P_\delta = 3R'_r\left|\underline{I}'_r\right|^2 - 3\Re e\left\{\underline{U}'_r\,\underline{I}'^*_r\right\} = \Delta P_r - P_r \qquad (6)$$

If we consider $\Delta P_r \approx s.\Delta P_s$, there is the following representation:

$$P_r = -s.P_s \qquad (7)$$

The mechanical power P_{wt} can be expressed with:

$$P_{wt} = 3\frac{1-s}{s}R'_r\left|\underline{I}'_r\right|^2 - 3\Re e\left\{\frac{1-s}{s}\underline{U}'_r\,\underline{I}'^*_r\right\} \qquad (8)$$

2.3. Operating mode

In subsynchronous operation the converter feeds power into the rotor. During oversynchronous operation, the rotor supplies power via the converter back to the grid.

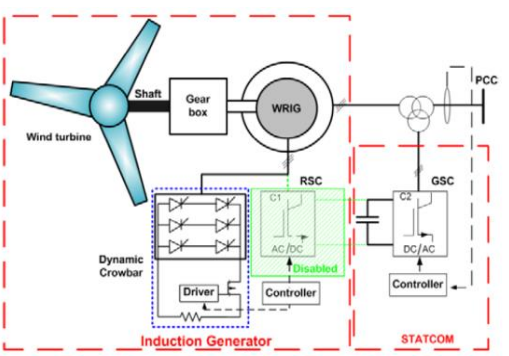


Figure 4. The method to controls and operates the wind turbine DFIG when there is a short circuit fault on the grid.[1]

When there is a short circuit fault on grid near the wind power plant, most of the stator power will be consumed at this point and then voltage of the power system will unbalance. When there is a short circuit fault, the power electronics are controlled according to a completely different operating mode from normal operation (as shown in Figure 4). During short circuit fault, the GSC is controlled to support the reactive power demand of the grid as a reactive power source (as a STATCOM) and decoupled operation. The RSC is disabled. A resistor bank, which is commonly known as the crowbar protection, is connected to the rotor of DFIG as an WRIG. At the same time, the DFIG power curve is changed to WRIG power curve (Figure 5).

The time of short circuit fault is not long enough for the wind speed and pitch angle to change. At the same time, the rotor is connected to the crowbar resistor, so the power in the rotor side (P_r) is consumed on these resistors. It is this reason that the active power characteristic of the WRIG passes through zero at the synchronous speed and is lower than the power characteristic of the DFIG.

In Figure 5, the WRIG power curves will decrease gradually as the $R_{crowbar}$ increases gradually.

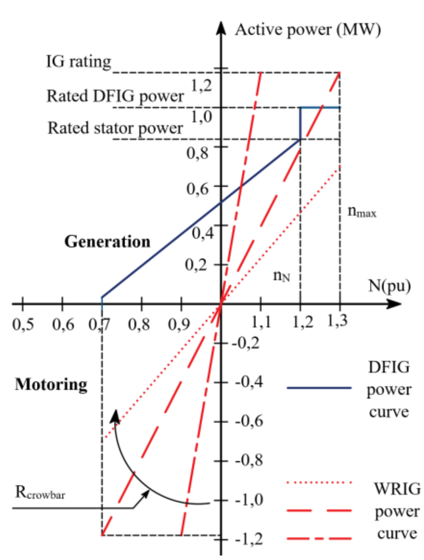


Figure 5. Active power characteristics of DFIG with crowbar resistor connected to rotor in case of short circuit fault on the grid.[1]

3. SIMULATION AND EVALUATION OPERATING MODE OF WIND POWER GENERATOR

3.1. Simulation operating mode of wind power generator with a short circuit fault on grid near the wind power plant

The wind generators at Phuong Mai 3 wind power plant are selected in this paper to survey operating mode of wind power generators in case of short circuit fault on the grid near this plant.

The wind generators in Phuong Mai 3 are DFIG in accordance with the study of the paper.

Table 1. Specification of wind turbine at Phương Mai 3 wind power plant.

Manufacturer	GAMESA EOLICA S.A.U	
Type of generator	DFIG	
Model	CR33-6P	
Stator connection	Δ	
Rotor connection	Y	
Rated voltage	690 V	
Rated frequency	50 Hz	
Rated speed	1120 rpm	
Maximum speed	1800 rpm	
Rated power	3465 kW	
Rated power	3450 kW	3615 kW
Power factor	0,95 1 0,95	0,9842 1 0,9842
Max. amb . temp	35 °C	30 °C
Short – circuited power	3200 kW	
Short – circuited power factor	0.88	
Poles N°	6	
Momen of inertia	300 kgm^2	

Data of wind power simulation in Matlab is shown in Table 1.

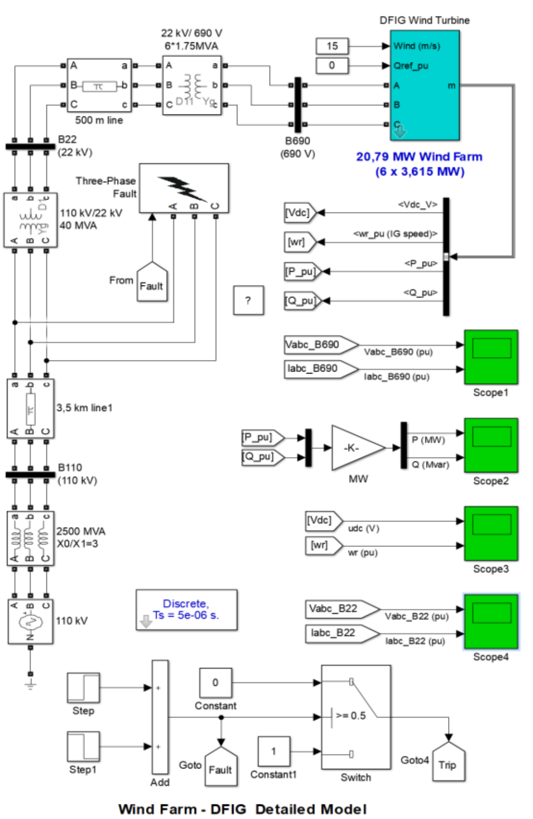


Figure 6. The wind power system simulated in Matlab/ Simulink.

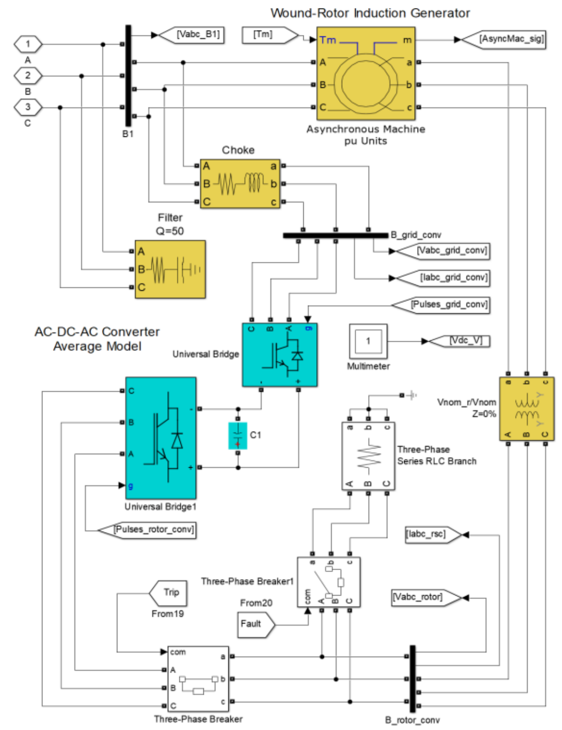


Figure 7. The DFIG with the rotor connected to crowbar resistor.

In the simulation (Figure 6), there are 6 wind turbines and the total active power is 20,79 MW. The output voltage of all generators is 690V. These poles are connected to a 22kV system via a 22kV / 690V transformer. Then the 22kV system is connected to a 110kV system through a 110kV / 22kV transformer. The length of 110kV line to the connection point is 3.5 km. The grid in the simulation has a frequency of 50Hz.

In this simulation model, an operation method as shown in section 2.3 (as shown in Figure 7) is used. This simulation is intended to evaluate low voltage ride-through fault and transient stability.

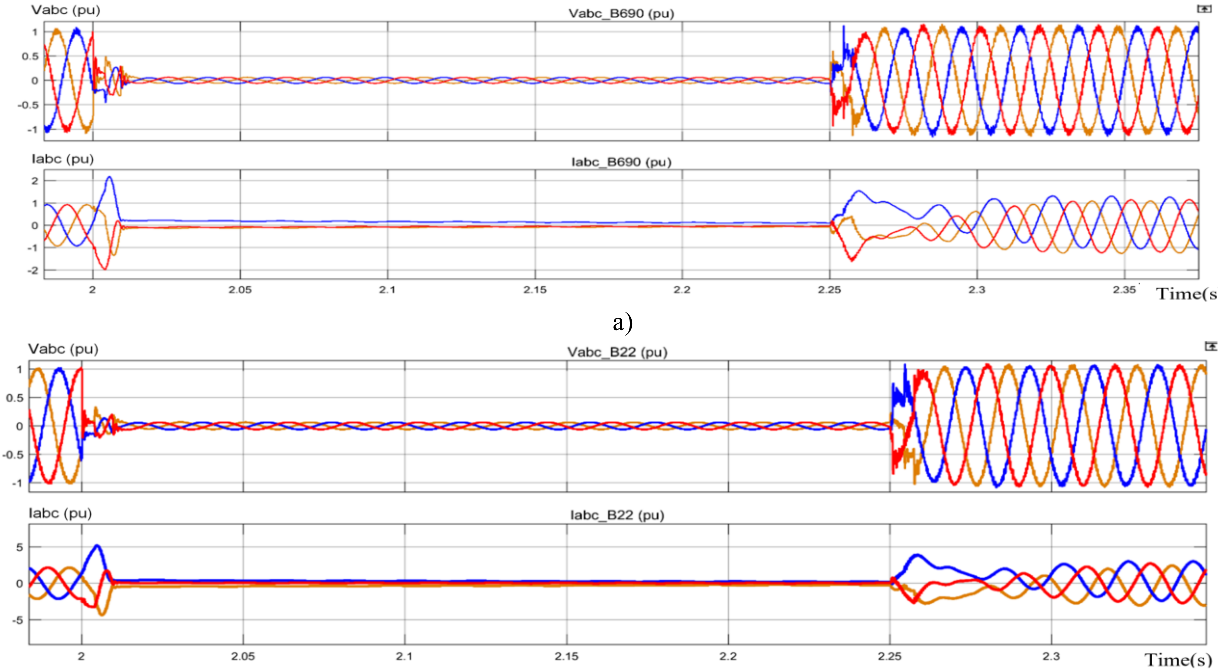
3.2. Results and discussion

Operating modes of wind power generators are simulated in 5s. The time of short circuit fault on the grid is 0,25s and the wind speed is 15m/s.

Figure 8 and Figure 9 show the power, voltage, current of DFIG when it has a short circuit fault on grid near the wind power plant.

Figure 8 shows that operating mode of DFIG is changed. Hence, the low voltage fault of the grid is supported to ride-through. So, the rotor is connected to crowbar resistor is a useful solution. In addition, the voltage of the grid is recovered quickly after short circuit fault is cleared.

Power characteristics (in Figure 9) in interval from 0.2s to 0.25s show that the active power was dissipated in the crowbar resistor. Therefore, the speed of rotor is controlled at the appropriate value as the speed characteristic (in Figure 10). This operation method makes the system easy to ensure transient stability.



a)

b)

Figure 8. a) Line-voltage and line-current in busbar B690; b) Line-voltage and line-current in busbar B22.

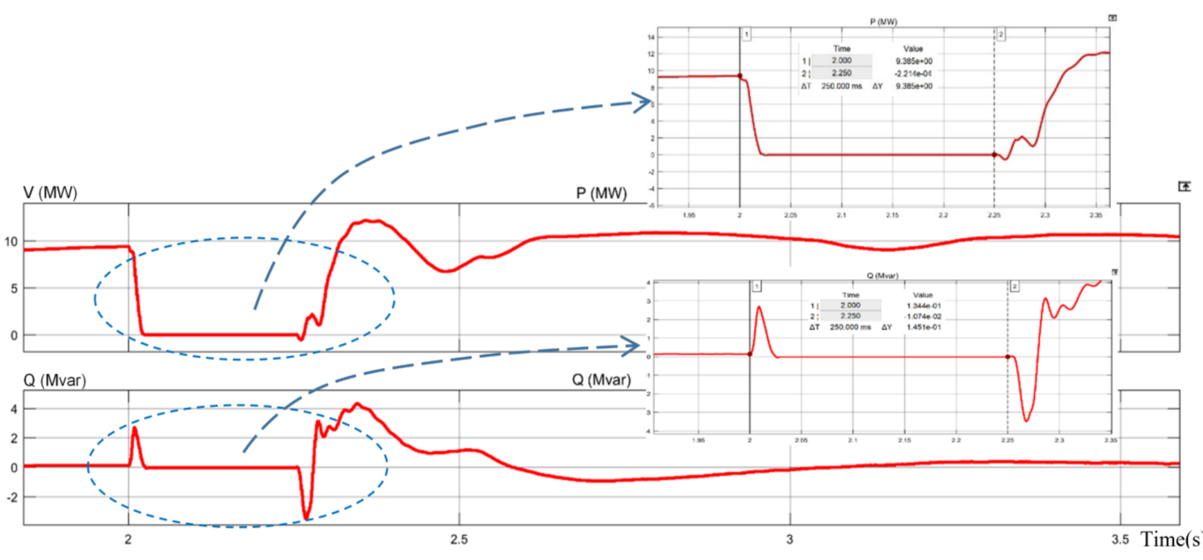


Figure 9. Active power curve and reactive power curve when short circuit fault on grid near the wind power plant.

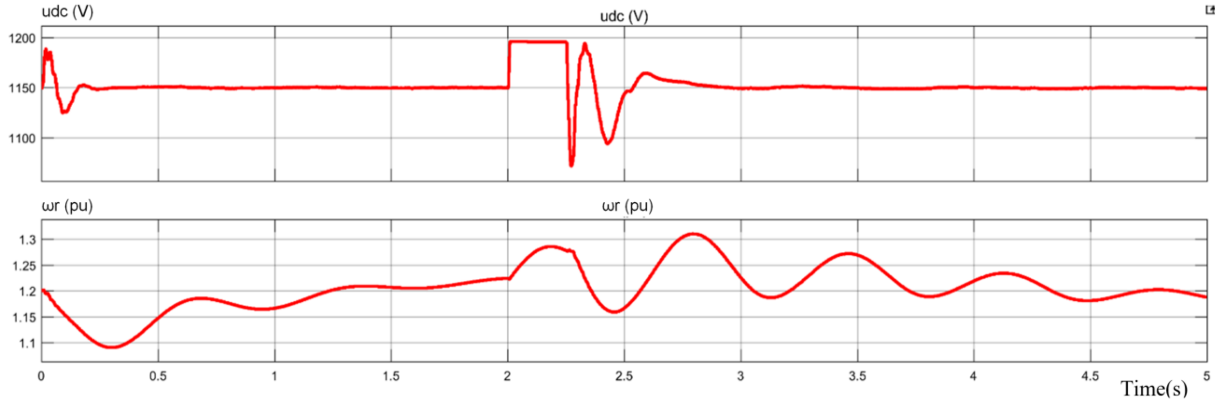


Figure 10. Voltage curve in capacitor u_{dc} and rotor speed curve.

According to Figure 9, power curve is changed to a new steady state, drop a lot from 2s to 2,25s and restore the state almost before the short circuit fault. The time to restore the state is short, so the wind generators are not cut off from the grid and ready to work again after short circuit fault is cleared.

Besides, during the short circuit fault, the GSC supplies reactive power to grid for the purpose of improving stability of this grid. This result is shown in voltage curve u_{dc} at capacitor (Figure 10) and reactive power curve Q (Figure 9).

Other parameters such as voltage and current are also changed a lot. In Figure 8, the voltage curve drops so much, at the same time the current is fluctuated but it keeps low (different from current is height of normal short circuit). This is the result of the transition from DFIG to WRIG. This helps the system minimize the adverse impact when height current flowing in electrical equipment in power systems and fault point.

To optimize the efficiency of operations of the wind turbine at the time short circuit fault on grid near the wind power plant, other parts of it are calculated and controlled according to measuring equipment in this turbine.

When the short circuit fault is cleared, the power system is kept working and ensure service reliability. According to these simulation results, the new operating mode is different from the first one, but it is not much and it assures service reliability.

4. CONCLUSIONS

The paper has analyzed the operation method of DFIG in modes before, during and after a short circuit fault. The special feature of this operation method is that during a short circuit fault, the DFIG is converted to WRIG by the crowbar resistor connected to the rotor and the RSC is disabled.

In the paper, this operation method is tested by simulation on Matlab/ Simulink. The simulation results show that:

- It is this conversion that the amount of active power transmitted to the grid is reduced to a very low level. As a result, the short-circuit current is limited and the rotor speed increases only within the permissible range.

- Thanks to this operation method, generators support the grid to ride through the low voltage fault and ensures good transient stability. Thanks to this, after the fault is cleared, the system quickly achieves a pre-fault operating state.

The results of the paper contribute to the affirmation that the wind generators in the wind power plants can support good transient stability and contribute to reliable grid operation.

REFERENCES

1. L. Meegahapola, T. Littler, D. Flynn. Decoupled-DFIG fault ride-through strategy for enhanced stability performance during grid faults, *IEEE transactions on sustainable energy,* **2010**, *1*(3), 152–162.

2. P. Huang, M. S. E. Moursi, and S. A. Hasen. Novel Fault Ride-Through Scheme and Control Strategy for Doubly Fed Induction Generator-Based Wind Turbine, *IEEE transactions on energy conversion*, **2015**, *30*(2), 635–645.

3. M. Hossain, M. H. Ali. Transient stability improvement of doubly fed induction generator based variable speed wind generator using DC resistive fault current limiter, *IET renewable power generation*, **2016**, *10*(2), 150 – 157.

4. S. M. Ali, M. Jawad, Z. Ullah, B. Khan. Fault-ride-through schemes of grid-interfaced DFIG: a comparative study under symmetrical grid faults, *2017 International symposium on recent advances in electrical engineering (RAEE)*, Islamabad, Pakistan, 2017.

5. R. Islam, J. Hasan, R. R. Shipon, M. A. H. Sadi, A. Abuhussein, and T. K. Roy. Neuro fuzzy logic controlled parallel resonance type fault current limiter to improve the fault ride through capability of DFIG based wind farm, *IEEE access*, **2020**, *8*, 115314–115334.

6. M. Q. Duong, F. Grimaccia, S. Leva, M. Mussetta, and K. H. Le. A hybrid fuzzy-pi cascade controller for transient stability improvement in DFIG wind generators, *2016 IEEE international conference on fuzzy systems (FUZZ-IEEE)*, Vancouver, BC, Canada, **2016**, 1733–1739.

7. T. T. Chuong. Study of voltage collapse charactiristics in grid connected wind power plant, *Science & technology development*, *14*(K2- 2011), 80–93.

8. G. Michalke. *Variable speed wind turbines - modelling, control, and impact on power systems*, PhD thesis, Riso National Laboratory, Denmark, 2008.

9. V. Akhmatov. *Analysis of dynamic behaviour of electric power systems with large amount of wind power*, Technical University of Denmark, 2003.

10. A. D. Hansen, F. Iov, F. Blaabjerg, L. H. Hansen. Review of contemporary wind turbine concepts and their market penetration. *Wind engineering*, **2004**, *28*(3), 247–263.

11. A. D. Hansen, G. Michalke. Fault ride-through capability of DFIG wind turbines, *Sciencedirect*, **2007**, *32*, 1594–1610.

12. P. Tourou, C. Sourkounis. *Review of control strategies for DFIG-based wind turbines under unsymmetrical grid faults*, 2014 Ninth International conference on ecological vehicles and renewable energies (EVER), IEEE, Monaco, 2014, 1–9.