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A New Synchronization Method of Double Fed Induction Generator Wind Turbines to the Grid

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Authors' contributions

This work was carried out in collaboration between all authors. Author MN designed the study and suggest the method, wrote the protocol and wrote a draft of the manuscript. Author MM performed the simulation and wrote the manuscript and Author EW managed the project, suggested the idea and finalized the manuscript.

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ABSTRACT

Meeting grid code requirement creates an obligation to smart WTs disconnection following some electrical or mechanical events. Increasing the penetration level of wind turbines (WTs) in different voltage levels of the network have a major effect on this condition. In this regard, soft and rapid synchronization control of doubly fed induction generator (DFIG) to reduce the dynamic and transient effects of DFIG on a smart grid is very important. This paper gives a review on WTs power generation and a basic requirement to operate in a stable manner in connection to the network at first. After that, different startup and synchronization methods will be described. Then, a new synchronization method for grid connection of DFIG driven by WT is proposed. In this method, the rotor side converter is synchronized with the induced voltage at the rotor winding of DFIG while the stator windings have been connected to the grid and the rotor accelerates normally with the wind torque. This startup process is soft and the synchronization is carried out between two low voltages

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with very low frequency and may overcome some difficulties and limitations of previous methods since it uses the rotor side converter as power electronics switches instead of the mechanical circuit breaker at stator side and causes the synchronization to be more accurate and controllable. The proposed method is evaluated with EMTDC/PSCAD simulation to show the performance of soft starting synchronization with lower electrical transients in comparison with traditional methods.

Keywords: Doubly fed induction generator; variable speed wind turbine; startup; grid synchronization.

LIST OF ABBREVIATIONS AND SYMBOLS

P_{s-oc} *: The open circuit of stator active power*
Q_{s-oc} *: The open circuit of stator active power*
P_s *: The stator active power*
P_r *: The rotor active power*
$J_{G,T}$ *: The momentum of inertia of the turbine and generator*
ω_m *: The angular frequency of the mechanical speed*
T_{wind} *: The wind torque*
T_e *: The electrical torque*
k_{MD} *: The mechanical damping*
R *: The blade radius*
P *: The air density*
$\boldsymbol{\beta}$ *: The pitch angle*
$\boldsymbol{\lambda}$ *: The tip speed ratio*
$c_p(\lambda,\beta)$ *: The wind power coefficient*

1. INTRODUCTION

Thanks to emerging distributed generation technology, the structure of traditional power systems has been changed and the renewable energy resources as the main source of electrical energy near the loads play the important roles in new power systems [1-2].

In the recent years, the wind energy has been developed more than other renewable energy technologies and may have higher capacity comparing with other renewable energy resources for each individual unit [3].

Wind energy conversion systems (WECS) are used in the fixed and variable speed categories. The fixed speed turbines have lower initial prices but they have lower efficiency, higher mechanical stress and higher maintenance cost. The variable speed turbines (VSWTs) can give more energy from the wind rather than the fixed speed type due to capabilities of receiving energy in the different speed by using power electronics converters [4].

The VSWTs are divided into two groups: partial and full nominal power electronics converters. The second group is developed from several hundred KWs to a few MWs capacity using DFIG [5-7]. VSWT-DFIG is gaining more attention among another type of WTs due to its advantages such as more efficient and more reliable in the intermittent nature of WTs. Two power electronic converters are used with back to back connection in the VSWT- DFIG as shown in Fig. 1. The Rotor Side Converter (RSC) is affected by mechanical speed and controls the DFIG powers, and the Grid Side Converter (GSC) controls the DC link voltage and should track its output power from RSC.

According to German Wind Energy Association (BWE) report in 2017, the total installed capacities of onshore and offshore WTs have reached to 50 GW and totally, 27,914 wind power plants generate clean energy throughout Germany [8]. This large and considerable capacity is about half of the peak power. A large amount of these powers generated in the north of Germany by WTs and after transportation over greater distances will be available for electricity markets in this country and Central Europe. This power transportation through large distance transmission lines may affect the stability of the system and may cause to WTs outage in some special cases [9]. In this situation, WTs should be reconnected to the grid automatically.

Due to increasing the number of wind powers installation in future and increasing penetration level of DGs, application of improved automatic FRT capability to reduce the number of disconnections, more WT disconnections due to the policy of smart grids interconnection across the EU countries, suffering WTs from low voltage ride through (LWRT) and the disconnection of the DFIG according to grid code requirement, the start up and synchronization process of WTs are very important. This process should not exert transient and dynamic effects on this stable system [10].

Intermittent nature of wind farms in electric power generation and having non-coincident loads may lose the synchronous stability of WTs due to frequency and/or voltage deviations in electrical side. In this process, a stable equilibrium of rotor speed under frequency/or voltage deviation accelerates or decelerates the rotor shaft and if the kinetic energy stored in the rotating mass of WTs cannot support the electrical power deviation, WT should be disconnected from the network. Although the majority of the WTs are connected to the medium voltage grid, large offshore wind farms are connected to the high voltage network which their capacities are constrained due to reliability and security reasons [11]. To overcome problems relating to the direct consequence of connection and disconnection of WTs to the grid, new proper methods of control and adaptations in the startup and synchronization need to insure the stable operation of WTs.

Unidirectional power flow from WTs to the network may have some benefits and drawbacks from control and system's operation point of view and may impact on system stability which also may cause to WT disconnection [12].

In Germany, the Grid Code requirement for WTs has been introduced in 2003 for the first time to have a secure operation of the system. Then, in order to investigate the effect of increasing WT capacity on the network in future, these codes were reconsidered in collaboration with WTs manufactures, German transmission grid operators and some research institutes. The results implied that the current grid codes need to be updated [13]. This reconsideration suggests the increase of FRT capability by introducing new technologies, reconnection and continuation of power generation in the shortest possible time following WT tripping, providing ancillary voltage and frequency controllers in islanding operation mode and the establishment of monitoring and intelligent protection device to fulfil the grid code requirements and guarantee fast recovery of normal operation.

According to new grid code voltage support, the secondary voltage or frequency controller should be stimulated to keep the WT terminal voltage with a maximum 10% voltage variation in current operating [14]. From the frequency grid code requirement point of view, WTs should stay in the connection state operation in the frequency range between 47.5-51.5 Hz. Although all these grid codes prevent to unnecessary disconnection of WTs from the network and try to continue the stable operation of WTs, the startup and synchronization process are still a very important issue in this area.

A lot of studies have been done on modelling, control and standardization of the VSWT with DFIG [15-18] but, there are few papers about its synchronization and startup [19-27]. On the DFIG synchronization methods, the most important issue is minimizing the electrical transients and mechanical stress. This problem will be more important as DGIG capacity increases; since it may have considerable effects on stator current which may not meet the requirements of the grid and therefore, the grid codes enforce the WECS to follow some limits during the grid connection time [19,22].

The soft starter may be used to reduce the electrical and mechanical stress for synchronization process of DFIG to grid after disconnection. In this case, the rotor windings are shorted together, the generator will start like a squire cage induction generator, but the turbine cost increases in this method [20].

Currently, there are two main methods for DFIG startup. In a first way, DFIG starts up as a motor and receive energy from the grid and the second method is that using the wind energy for generator acceleration while the pitch angle is controlled to reach the generator speed to synchronous speed. The second method has some superiorities than the first method and more literature are available about this method [19-24]. In [23], the combination of two methods is used by the authors.

The general startup procedure has seven steps: 1) Keeping the stator windings as open circuit, 2) Initializing the DC voltage of converters with GSC, 3) Turbine acceleration while the mechanical brakes are open, 4) Controlling the turbine speed with the pitch angle controller, 5) Voltage injection in the rotor winding with RSC, 6) Controlling the RSC voltage for synchronizing the stator voltages with the grid voltage (amplitude, phase and frequency), 7) Closing a mechanical circuit breaker for connecting the stator windings to the grid as shown in Figure 1 [6,19-24]. The controller must change the controller setting and configuration from voltage synchronization mode to power controller mode very fast after the synchronization in the conventional method. This procedure causes some mechanical stress and electrical transient [20-21].

In the conventional methods, the rotor voltage is produced by RSC and this voltage inherently has harmonics; on the other hand, the stator windings are open circuit during synchronization and are affected by the RSC. So, the induced stator voltage is much distorted. This subject deteriorates the stator voltage detection process (phase, amplitude and frequency) for synchronization [19-20,24-25].

Another important issue is that the generator must be controlled near the synchronous speed by the pitch angle controller. This controller is relatively slow and does not have enough accuracy for electrical synchronization, moreover, some WECS's do not have pitch angle controller; So, the speed control will be difficult in this method especially in the high wind fluctuations [19,21].

The conventional method needs a mechanical circuit breaker in the stator windings with a fast closing response also. Limitation of RSC capacity to 30% of nominal power is a further problem for the conventional startup because the mechanical speed is zero at the beginning of startup, the RSC must generate exactly the nominal frequency of grid whereas the RSC is designed for low frequency and low power operation [19,24]. The conventional method needs to estimate the generator speed and flux that their detections are discussable in the transient state when a fast startup needs [20]. Some control algorithms are introduced for transient and stress reduction of the conventional startup [22,24-26].

Although the stator current has not been shown in these papers for electrical transient comparison in the synchronization time [24-25], it is evidence that the stator current transient is high in the conventional methods.

A novel and effective method for startup of DFIG is proposed in this paper that reduces some mentioned problems. This method is based on synchronization at the rotor side in low voltage amplitude with low frequency. The main advantage of the proposed method is that it uses the RSC as power electronic switches for synchronization of DFIG to the grid. The superiority of the proposed algorithms is that the introduced algorithm is fully compatible with Fault Fide Through (FRT) requirements that the WT must remain connected to the grid during the grid faults and are under investigation by authors. The discussed algorithm has significant performance during and after the grid fault.

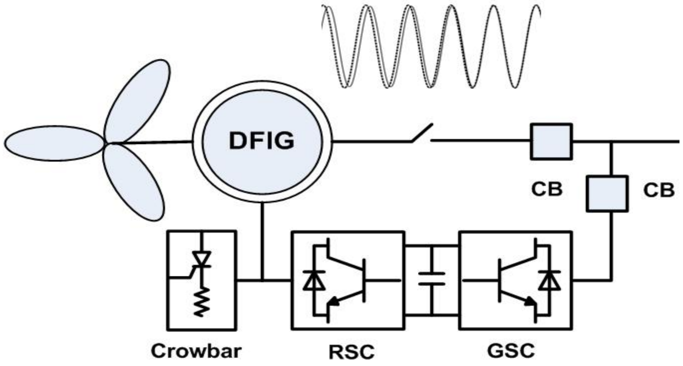

Fig. 1. Variable speed WT with DFIG

2. ANALYTICAL INVESTIGATION OF THE PROPOSED METHOD

In the proposed method, the stator winding is connected to the grid while the rotor winding is open. As the grid voltage induces a three-phase voltage to the rotor winding, the RSC produces another three-phase voltage and try to synchronize it with the induced rotor voltage. The proposed method has four steps for synchronization: 1) Connecting the stator windings to the grid (while the rotor windings are open circuit), 2) Initializing the DC voltage of converters with GSC, 3) Opening the mechanical brakes for turbine acceleration, 4) Creating the RSC voltage for synchronizing with the rotor induced voltage (amplitude, phase and frequency).

2.1 Connecting the Stator Windings to the Grid

The stator is connected to the grid while the rotor windings are open via keeping the RSC switches in off state. The electrical transient of the stator current is low because the rotor winding is open. The electrical torque is zero because the rotor current is zero. The equivalent circuit of DFIG in the stator side is shown in Fig. 2.

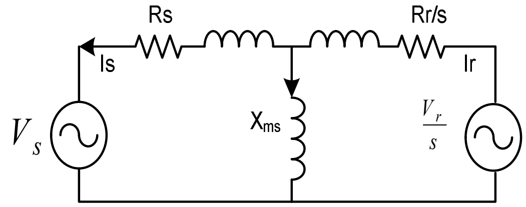

Fig. 2. The equivalent circuit of DFIG from the stator side

The stator winding will have a low current, low active and reactive power as (1):

$$P_{s-oc} = \frac{V_s^2}{R_s^2 + (X_s + X_m)^2} R_s \tag{1}$$

$$Q_{s-oc} = \frac{V_s^2}{R_s^2 + (X_s + X_m)^2} (X_s + X_m) \tag{2}$$

Where V_s is the stator voltage, R_s is the stator resistance, X_s is the stator reactance, and X_m is the generator magnetizing reactance.

2.2 Initializing the DC Voltage of Converters with GSC

The DC voltage of the capacitor is initialized by the GSC in the rectifying mode. This step is the same as in the conventional method. If synchronization is done after operation of the crowbar protection for FRT, the DC voltage initializing will not need.

2.3 Opening the Mechanical Brakes for Turbine Acceleration

The generator will accelerate freely by the wind energy with releasing the mechanical brakes. The mechanical speed and torque will be as (3), where T_{wind} is the wind torque, and $J_{G,T}$ is the inertia moment of the turbine and generator and k_{MD} is the mechanical damping coefficient.

$$J_{G,T} \frac{d\omega_m}{dt} = T_{wind} - k_{MD}\omega_m \tag{3}$$

The wind energy depends on the wind speed and the air density. The wind torque will be calculated as (4)-(5) [6]:

$$T_{wind} = 0.5\rho\pi R^2 V^3 C_p(\lambda,\beta) \big/ \omega_m \tag{4}$$

$$\lambda = R \cdot \omega_m / V_w \tag{5}$$

Where V_w is the wind speed (m/s), R(m) is the blade radius, ρ is the air density, $\boldsymbol{\beta}$ is the pitch angle, $\boldsymbol{\lambda}$ is the tip speed ratio, ω_m (rad/s) is the mechanical speed and $c_p(\lambda,\beta)$ is the wind power coefficient. The Van der Hoven model is used to wind modelling here as (6) to (7) [6].

$$c_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{6}$$

$$\begin{gathered} \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \\ c_1 = 0.5176,\ c_2 = 116,\ c_3 = 0.4 \\ c_4 = 5,\ c_5 = 21,\ c_6 = 0.0068 \end{gathered} \tag{7}$$

The pitch angle of blades is an independent parameter that is controlled to have a proper situation in different wind speeds. As the mechanical shaft of the rotor is accelerated by the wind torque, the amplitude and frequency of the induced voltage to the rotor windings decrease until they reach zero at the synchronous speed.

This step is used only when the turbine speed is zero at the initial startup. When the turbine is disconnected from the grid at the grid disturbances, this step is not necessary actually. The synchronization can be done every speed with the proposed method.

2.4 Creating the RSC Voltage for Synchronizing to the Rotor Induced Voltage

The amplitude and frequency of the rotor three-phase winding voltage tend to decrease while the rotor speed increases. As these voltages reach zero, RSC is connected to them. The advantage of the proposed method is firing the RSCs switches in low amplitude and low frequency which brings low electrical transient and low mechanical stress during synchronization and after that. The synchronous controller is shown in Fig. 3. The main controller is connected to RSC after synchronization.

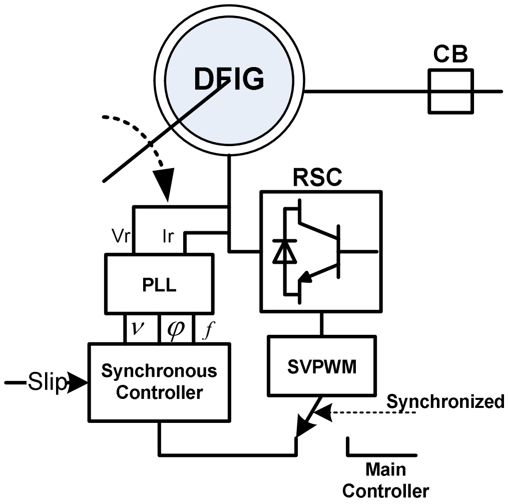

Fig. 3. The synchronous controller

After connecting the RSC to the rotor windings, the equation (3) changes to equation (8) which T_e is the electromagnetic torque as equation (9).

$$J_{G,T}\frac{d\omega_m}{dt}=T_{wind}-T_e-k_{MD}\,\omega_m \tag{8}$$

$$T_e=1.5pL_m\,\mathrm{Im}(i_s\,i_r^*) \tag{9}$$

3. CALCULATING THE STEADY STATE OPERATION POINT

A large amount of electromagnetic transient torque may be created while the stator has been connected to the grid during synchronization process and the RSC is connected to rotor windings due to stator transient current of DGIG as indicated in (3) and (8) and the relation of stator and rotor currents to electromagnetic torque. Therefore, the only synchronization of the induced voltage to grid voltage will not be sufficient for transient suppression.

To suppress the effect of this transient electromagnetic torque or electrical transient, the steady-state operating point is calculated in the proposed method online, and DFIG is synchronized at this operating point. Connecting RSC to the rotor winding at the steady state operation point causes to the elimination of the transient part of currents theoretically. This is similar to that the connection of a simple RL series load (with an initial current) to a voltage at a certain time (proper to steady-state condition) will cause to the elimination of the transient part of the current.

The steady-state parameters of DFIG can be calculated at each value of rotor speed. The rotor frequency calculates via measuring the induced rotor voltage while the rotor speed accelerates in the second step. The active power of the stator and rotor are as follow:

$$s=\frac{\omega_s-\omega_m}{\omega_s} \tag{10}$$

$$\begin{aligned}P_m&=P_s+P_r\\ P_s&=sP_r\end{aligned} \tag{11}$$

Where, P_m is the total wind power, P_s is the stator active power, P_r is the rotor active power, and s is the slip.

Having the stator active and reactive powers, the amplitude and phase of the stator current is calculated from (12)-(13).

$$P_s=3\,\mathrm{Re}(V_s I_s^*) \tag{12}$$

$$Q_s=3\,\mathrm{Im}(V_s I_s^*) \tag{13}$$

The amplitude and phase angle of the rotor voltage is calculated via (14) and (15).

$$I_r = \frac{V_s - R_s I_s - j\omega_s (L_{\sigma s} + L_m) I_s}{j\omega_s L_m} \tag{14}$$

$$\frac{V_r}{s} = \frac{R_r}{s} I_r + j\omega_s L_{\sigma s} I_r + j\omega_s L_m (I_s + I_r) \tag{15}$$

Therefore, the rotor voltage is calculated instantaneously based on the mechanical speed. This procedure is shown in Fig. 4.

As shown, all the steady-state parameters of DFIG are calculable via measuring the rotor voltage and knowing the stator reactive power.

Block diagram of a proposed method for calculation of steady-state parameter instantaneously is shown in Fig. 5.

As shown, the required synchronization of the rotor voltage is calculated instantaneously with the rotor acceleration. The advantage of the proposed technique is that the calculated parameters are equal to the steady-state values for each operation point. It means that the proposed method can synchronize the generator at each rotor speed independent of conventional method limits.

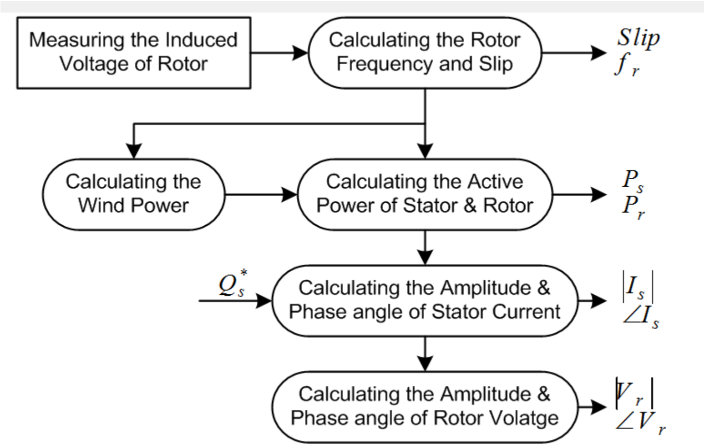

Fig. 4. Calculation the steady state operation point of DFIG instantaneously

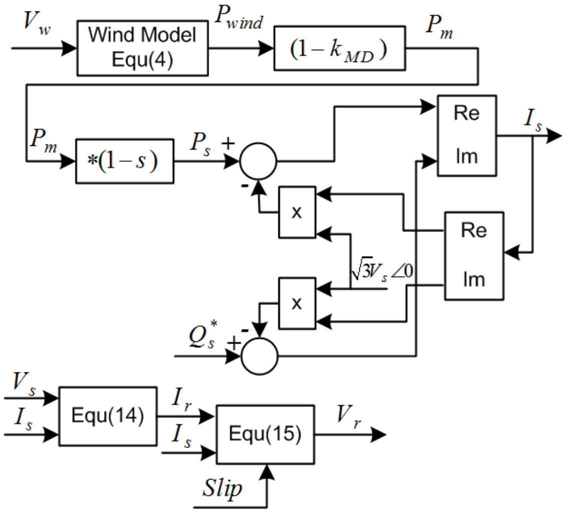

Fig. 5. A schematic block diagram of steady-state parameter calculation

4. EVALUATION OF THE PROPOSED METHOD

The proposed method has been evaluated by the simulation time in PSCAD/EMTDC. A system containing a VSWT-DFIG used for evaluation is shown in Fig. 6. The parameters of VSWT-DFIG are shown in Table 1.

The stator current in the first step of the proposed method is shown in Fig. 7. The active and reactive powers of the generator in this step are shown in Fig. 8.

There is not any stress on mechanical parts because the electromagnetic torque is zero in this step. The maximum amplitude of the stator current during transient state is less than 1.0 pu. The second step is done normally.

Table 1. DFIG and turbine parameters used in simulation [14]

Parameters	Value
Rated power	2 MW
Rated voltage	690 V
Rated frequency	50 Hz
Stator / rotor turns ratio	3
Mechanical damping	0.01
Stator resistance	0.04 pu
Stator reactance	0.05 pu
Mutual reactance	2.9 pu
Rotor resistance (stator side)	0.17 pu
Rotor reactance (stator side)	0.15 pu
Number of poles pairs	2
Generator angular moment of inertia	2.9 s
Gearbox and blade angular inertia constant	2.1 s

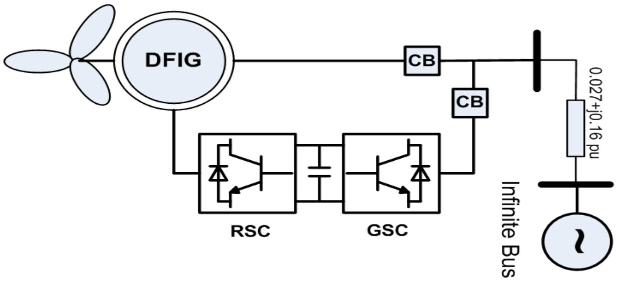

Fig. 6. Single line diagram of an evaluation system

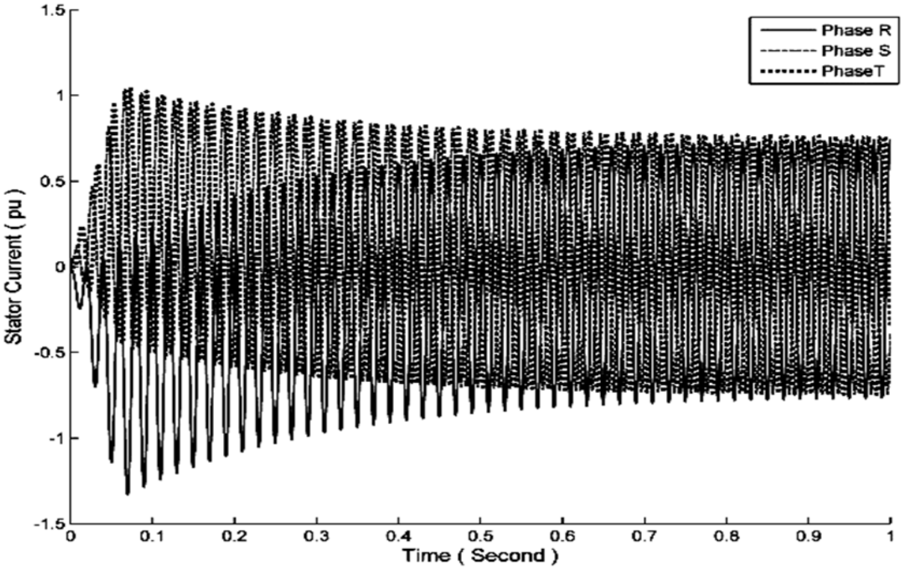

Fig. 7. The stator currents in the first step

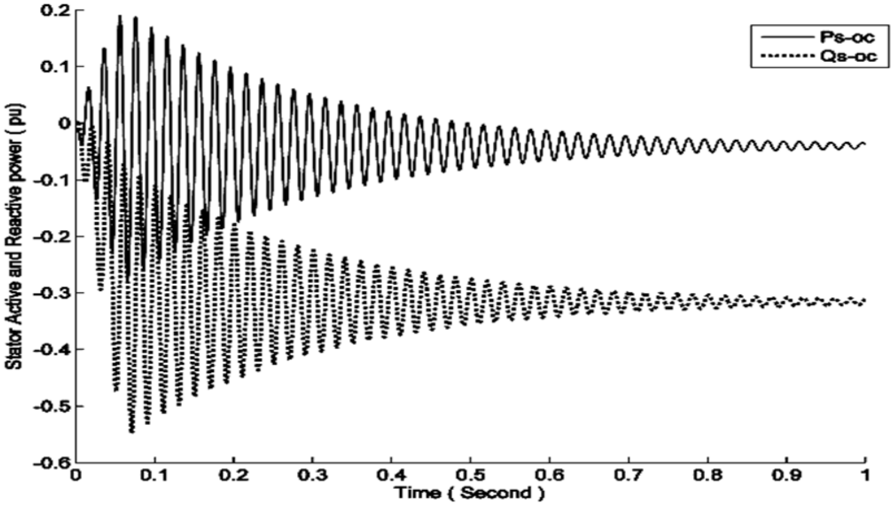

Fig. 8. The active and reactive power of stator winding in the first step

According to the third step, the speed and torque of the turbine increase and the rotor induced voltage start to decrease and at the synchronous speed, it will be zero. The amplitude and frequency of the rotor voltage increase for over synchronous speed as shown in Fig. 9 based on (3).

The important point in the proposed method is that the amplitude and frequency of the rotor induced voltage decreases with increasing the mechanical speed before synchronous speed as shown in Fig. 9. The amplitude and frequency of the rotor voltage will increase after passing through the synchronous speed.

The optimum time for connecting the RSC to the rotor windings is the synchronous instant that the rotor voltage is synchronous with the rotor induced voltage as shown in Fig. 10. Based on the mentioned point, synchronization near this time will have very low electrical transient.

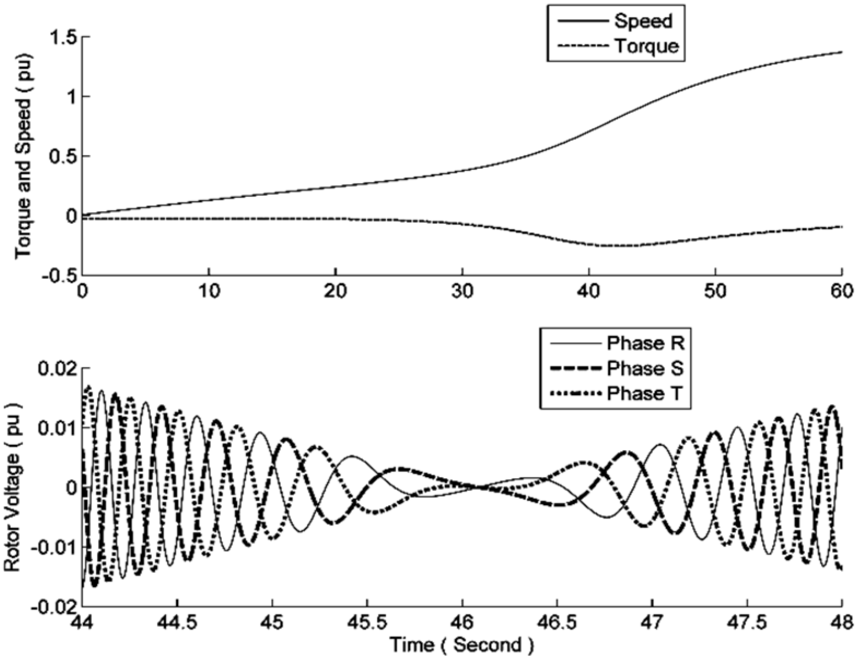

Fig. 9. The turbine speed and torque in the third step

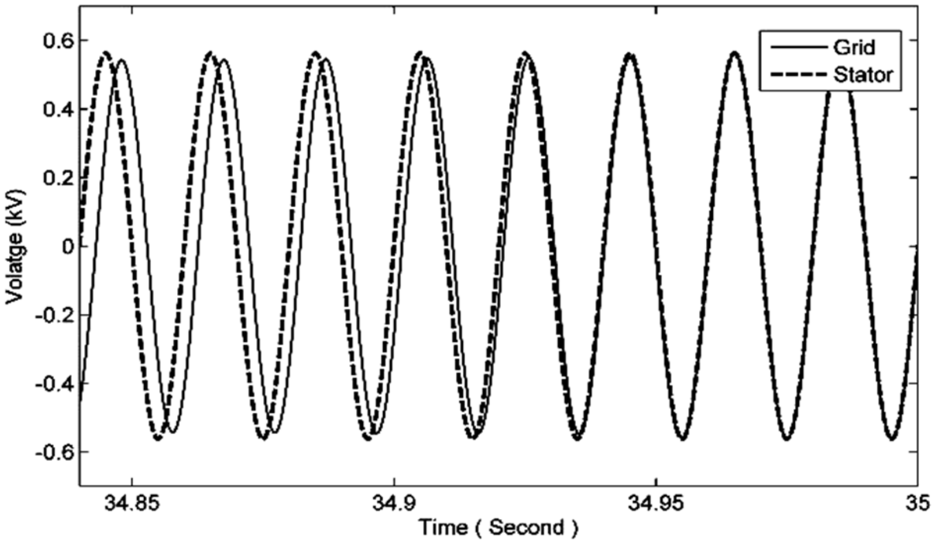

Fig. 10. Synchronization instant at the rotor side at 34.94 second

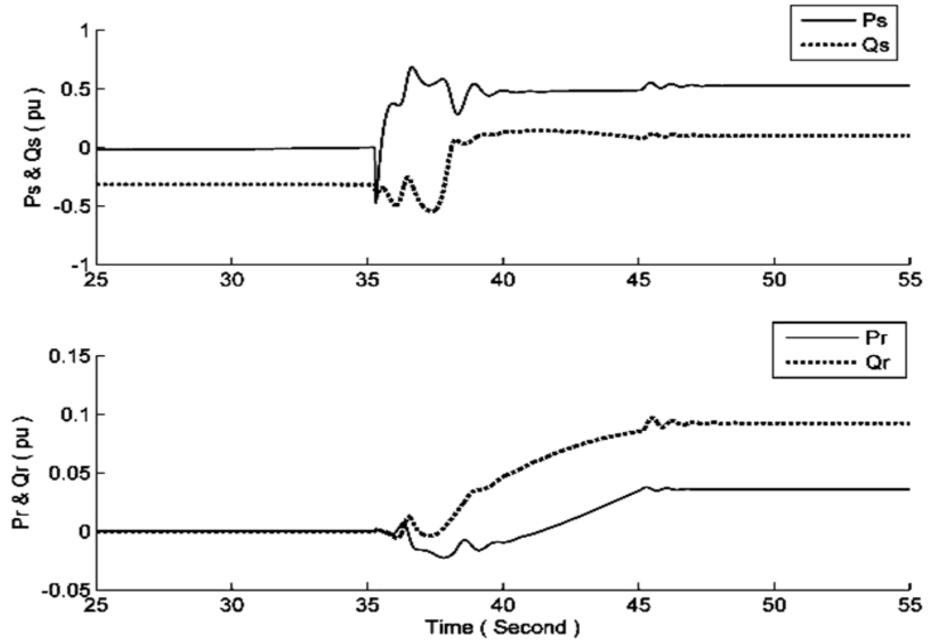

Fig. 11. The active and reactive power of generator synchronizing at 34.94 second

This situation is simulated as shown in Figs. 11 and 12 which the generator is synchronized at 34.94 seconds.

Although the transient current during synchronization time has not been shown generally in synchronization methods yet, the stator and rotor currents have high amplitude transient until to 4pu in the conventional methods [22]. Comparison of the conventional method with the proposed method is shown in Fig. 13.

Comparison of the proposed method with the conventional method shows that the proposed method has lower electrical transient and therefore, the mechanical stress is lower. As the proposed method is based on synchronization at the rotor side and completely is different from the

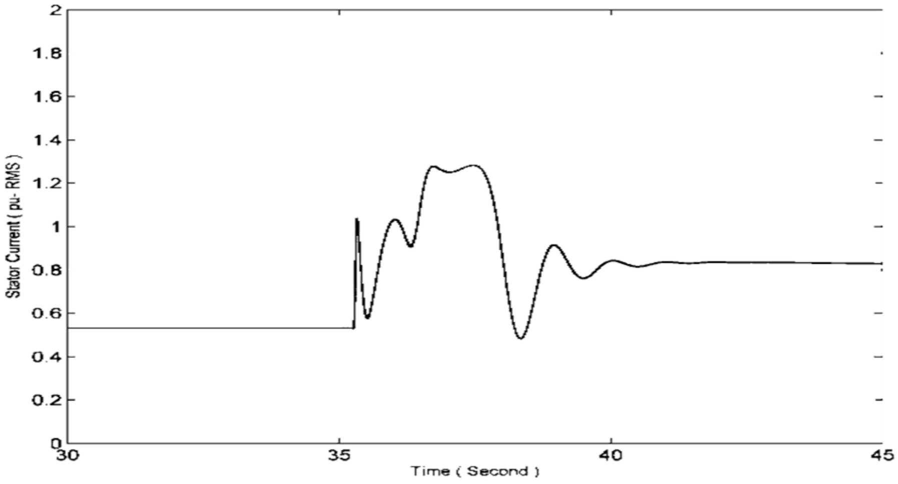

Fig. 12. The stator current of generator synchronization at 34.94 second

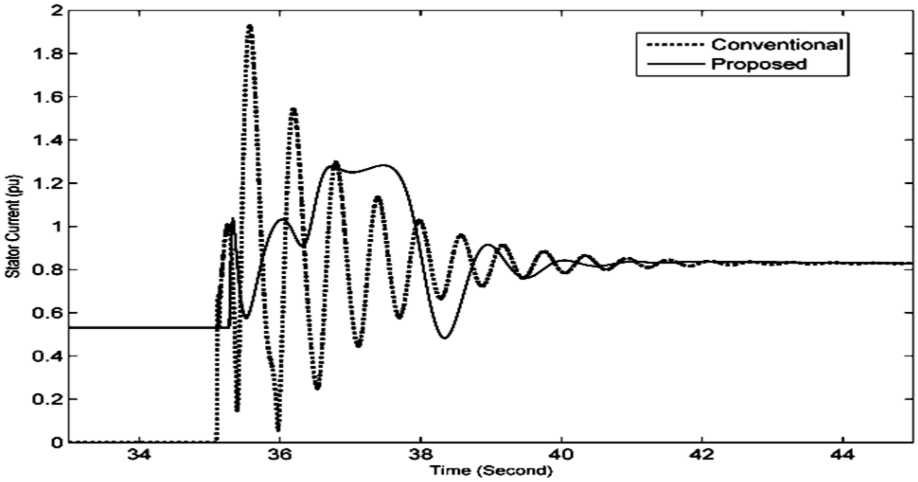

Fig. 13. Comparison the proposed method with the conventional method

conventional method. This paper only described the structure of a new synchronization method and the research on different control algorithms is continuing to improve the transient shown in Fig. 13.

5. CONCLUSION

A new simple method for synchronization of WECS-DFIG to grid based on rotor side rather than stator side is presented in this paper. It is shown that this new method has low electrical transient, low mechanical stress, enough speed and accuracy. All these advantages are due to the using power electronics switches of RSC instead of the mechanical breaker and synchronizing in the rotor side that has low voltage and low frequency. The controller must change reference power from zero to the final value in a smooth way after startup.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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