

Soft Starter Investigation on Grid Connection of Wind Turbines

¹F. Gharedaghi, ²M. Deysi, ³H. Jamali and ⁴A. Khalili

Department of Electrical Engineering, Genaveh Branch, Islamic Azad University, Genaveh, Iran.

Abstract: This work investigates grid connection of fixed-speed or two-speed wind turbine coupled with induction generator. A weak grid where a local customer and a wind turbine are supplied by the network by means of along overhead line has been defined and simulated using MATLAB\Simulink. This situation particularly evidences the impact of switching operations, mainly the start-up or the change between generator windings. Since the mechanical parameters defining the performance of the rotor speed are rarely given by manufacturers, a simplified structural analysis of a blade has been made in order to estimate the inertia time constant as a function of the blade length and weight. The performance and the logic control of the soft-starter gradually connecting the induction generator of the wind turbine to the rotor are also studied. During this transient, the third order model has been established as the best model to explain the performance of the induction generator. Expressions for the real and reactive power has been derived which show the strong influence of the voltage derivative on the reactive power. Finally, a controller has been designed that improve the open-loop linear control of the soft-starter. Simulation results show that the proposed control system to the soft starter of wind turbine works correctly.

Key words:

INTRODUCTION

In classical power systems, large power generation plants located at adequate geographical places produce most of the power, which is then transferred towards large consumption centers over long distance transmission lines. The system control centers monitor and control the power system continuously to ensure the quality of the power, namely the frequency and the voltage. However, now the overall power system is changing, a large number of dispersed generation (DG) units, including both renewable and non-renewable sources such as wind turbines, wave generators, photovoltaic (PV) generators, small hydro, fuel cells and gas/steam powered Combined Heat and Power (CHP) stations, are being developed (Najafi *et al.*, 201; Hana *et al.*, 2007) and installed. A wide-spread use of renewable energy sources in distribution networks and a high penetration level will be seen in the near future many places. E.g. Denmark has a high penetration (> 20%) of wind energy in major areas of the country and today 18% of the whole electrical energy consumption is covered by wind energy. The main advantages of using renewable energy sources are the elimination of harmful emissions and the inexhaustible resources of the primary energy. However, the main disadvantage, apart from the higher costs, e.g. photovoltaic, is the uncontrollability. The availability of renewable energy sources has strong daily and seasonal patterns and the power demand by the consumers could have a very different characteristic. Therefore, it is difficult to operate a power system installed with only renewable generation units due to the characteristic differences and the high uncertainty in the availability of the renewable energy sources.

The wind turbine technology is one of the most emerging renewable technologies. It started in the 1980's with a few tens of kW production power to today with Multi-MW range wind turbines that are being installed. This also means that wind power production in the beginning did not have any impact on the power system control but now due to their size they have to play an active part in the grid. The technology used in wind turbines was in the beginning based on a squirrel-cage induction generator connected directly to the grid. By that power pulsations in the wind are almost directly transferred to the electrical grid. Furthermore there is no control of the active and reactive power, which typically are important control parameters to regulate the frequency and the voltage. As the power range of the turbines increases those control parameters become more important and it is necessary to introduce power electronics (Najafi *et al.*, 2011) as an interface between the wind turbine and the grid. The power electronics is changing the basic characteristic of the wind turbine from being an energy source to be an active power source. The electrical technology used in wind turbine is not new. It has been discussed for several years (Sajedi *et al.*, 2011) but now the price produced kWh is so low, that solutions with power electronics are very attractive. One of the power electronic devices used in wind generation systems is soft starter. The soft-starter's function is to reduce the in-rush current by building up the magnetic flux slowly in the generator, thereby limiting the disturbances to the grid.

In this paper the role of soft starting of wind turbine on the starting current and torque will be studied.

Soft Starter:

The soft-starter is a simple and cheap electrical component used in fixed-speed wind turbines during their connection to the grid. The soft-starter's function is to reduce the in-rush current by building up the magnetic flux slowly in the generator, thereby limiting the disturbances to the grid. Without a soft-starter, the in-rush current can be several times the rated current, which can cause the generator to have a dangerously high starting torque that, in turn, causes severe voltage disturbances on the grid.

The soft starter contains two thyristors as commutation devices in each phase. They are connected anti parallel for each phase. The smooth connection of the generator to the grid, during a predefined number of grid periods, is achieved by adjusting the firing angle of the thyristors. The relationship between the firing angle and the resulting amplification of the soft-starter is highly nonlinear and is additionally a function of the power factor of the connected element. After the in-rush, the thyristors are bypassed in order to reduce the losses of the overall system.

If you switched a large wind turbine on to the grid with a normal switch (without the thyristors), the neighbors would see a brownout (because of the current required to magnetize the generator) followed by a power peak due to the generator current surging into the grid. You may see the situation in the drawing in the accompanying browser window, where you see the flickering of the lamp when you operate the switch to start the wind turbine. The same effect can possibly be seen when you switch on your computer, and the transformer in its power supply all of a sudden becomes magnetized. Another unpleasant side effect of using a "hard" switch would be to put a lot of extra wear on the gearbox, since the cut-in of the generator would work as if you all of a sudden slammed on the mechanical brake of the turbine.

Fixed Speed Configurations:

Wind turbines with fixed-speed configuration use induction generators directly connected to the grid. Because the grid's frequency is fixed, the speed of the turbine is dependent on the ratio of the gearbox and the number of poles in the generator. Most fixed-speed turbines, in order to increase the production of power, are equipped with a pole change generator which makes it operate at two different speeds. As large current can possibly rush in, a soft starter is utilized to limit the current during the start.

There are several things that one can be satisfied with induction generators. It has a robust design, there's no need for maintenance, well-enclosed, and produced in large series. And to top it all, it is a reasonably low price and strong enough to withstand overloads. The only problem about it, however, is the uncontrollable and excessive use of power.

Gearbox Design:

Gearbox is used to convert low-speed rotation from the input shaft of the rotor to high-speed rotation, which drives the high-speed shaft of the generator assembly. This [wind turbine] component is not an intrinsic part of the whole wind power technology. It is only utilized to increase the speed of the slow running main shaft to the speed required by mass-produced induction generators.

Turbine designers use either parallel shafts or planetary gear system. Parallel shaft gearboxes are the most conventional choice for most wind turbine operators. They eat up more space and weigh more than the other kind of gearbox but they are quiet when they operate. The planetary stage, in contrast, is used in low-speed shaft from the rotor where there is less noise.

Wind Farm Topologies:

In many countries energy planning is going on with a high penetration of wind energy, which will be covered by large offshore wind farms. These wind farms may in the future present a significant power contribution to the national grid, and therefore, play an important role on the power quality and the control of power systems.

Consequently, very high technical demands are expected to be met by these generation units, such as to perform frequency and voltage control, regulation of active and reactive power, quick responses under power system transient and dynamic situations, for example, to reduce the power from the nominal power to 20 % power within 2 seconds. The power electronic technology is again an important part in both the system configurations and the control of the offshore wind farms in order to fulfill the future demands (Gharedaghi *et al.*, 2011).

One off-shore wind farm equipped with power electronic converters can perform both real and reactive power control and also operate the wind turbines in variable speed to maximize the energy captured as well as reduce the mechanical stress and noise. This solution is shown in Fig. 1 and it is in operation in Denmark as a 160 MW off-shore wind power station. For long distance transmission of power from off-shore wind farm, HVDC may be an interesting option. In an HVDC transmission, the low or medium AC voltage at the wind farm is converted into a high dc voltage on the transmission side and the dc power is transferred to the onshore system where the dc voltage is converted back into ac voltage as shown in Fig. 3. For certain power level, an

HVDC transmission system, based on voltage source converter technology, may be used in such a system instead of the conventional thyristor based HVDC technology.

The topology may even be able to vary the speed on the wind turbines in the complete wind farm.

Another possible dc transmission system configuration is shown in Fig. 4, where each wind turbine has its own power electronic converter, so it is possible to operate each wind turbine at an individual optimal speed.

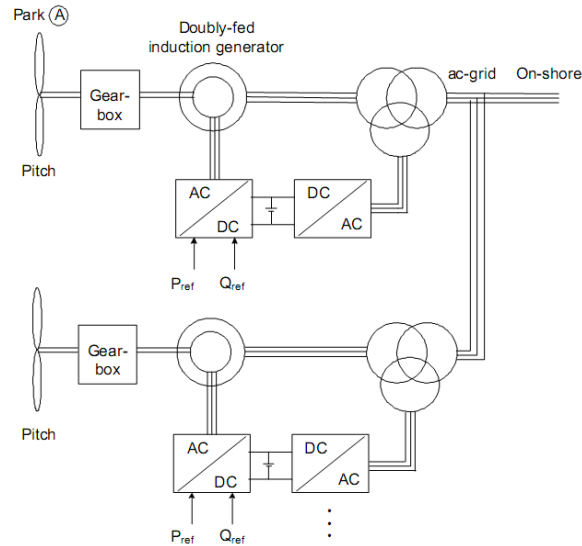


Fig. 1: Doubly-fed induction generator system with ac-grid (System A).

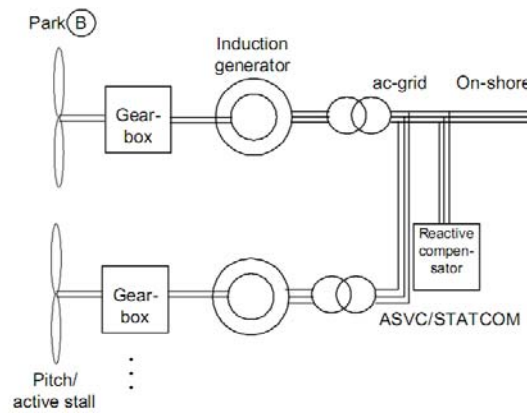


Fig. 2: Induction generator with ac-grid (System B).

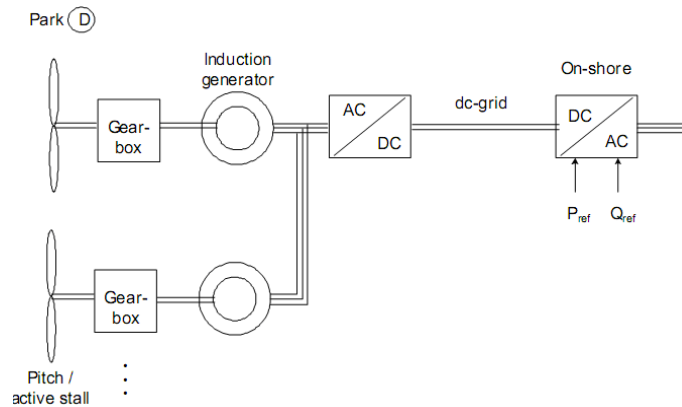


Fig. 3: Speed controlled induction generator with common dc-bus and control of active and reactive power (System C).

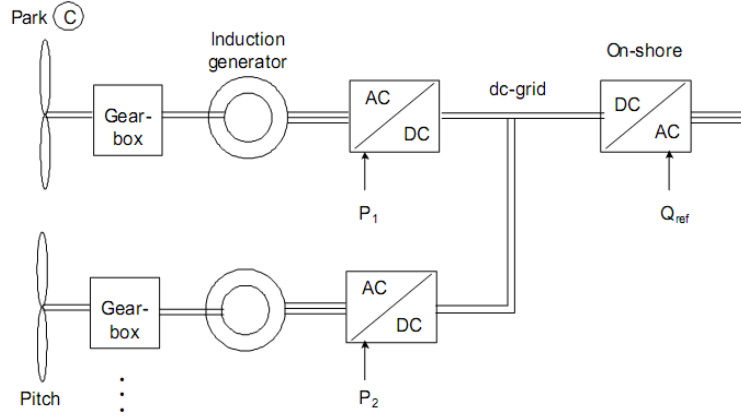


Fig. 4: Speed controlled induction generator with common ac-grid and dc transmission (System D).

Wind Model:

The model applied for this simulation is composed of three components and is described as follow (Hana *et al.*, 2007):

$$V_{WIND} = V_{BASE} + V_{GUST} + V_{RAMP} \quad (1)$$

Where V_{BASE} is the main component, V_{GUST} is the gust component and V_{RAMP} is the ramp component. The main component is a constant speed. ramp component can be expressed by a sinusoidal function which is considered as a composition of several different sinusoidal functions and gust component is considered as storm and sudden wind.

Wind Turbine:

the torque generated by wind blow is described by the following relations:

$$\lambda = \frac{\omega_M R}{V_{WIND}} \quad (2)$$

$$P_M = \frac{1}{2} \rho \pi R^2 C_p V_{WIND}^3 \quad (3)$$

$$T_M = \frac{P_M}{\omega_M} = \frac{1}{2} \rho \pi R^5 C_p \frac{\omega_M^3}{\lambda^3} \quad (4)$$

Where V_{WIND} is wind speed, r is the blades radius, ρ is the air density, ω_M is rotor angular speed and λ is the tip speed ratio (tsr), C_p is the power conversion factor which can be defined as turbine power in proportion with wind power and is related to blades aerodynamic characteristics. Resulted mechanical torque is applied as the input torque to the wind generator and makes generator to operate. Power conversion factor is expressed as the function of tip speed ratio λ as follow:

$$C_p = (0.44 - 0.0167\beta) \sin \frac{\pi(\lambda - 2)}{13 - 0.3\beta} - 0.00184(\lambda - 2)\beta \quad (5)$$

where β is blade's pitch angle. for a turbine with constant pitch, β is considered as a constant value, fig. 5 is C_p variations in terms of λ for different β values. in this paper β is considered zero where the C_p value would be 0.48 then.

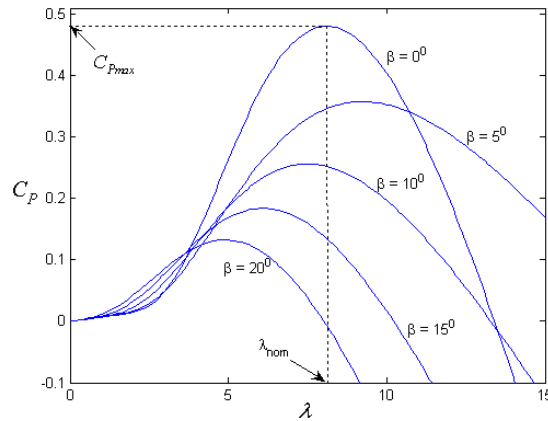


Fig. 5: C_p in terms of λ for different β values.

Table 1 shows the wind turbine parameters values applied in simulation.

Table 1: Wind Turbine Parameters.

Rated Power	15kw
Blade Radius	5.5m
Nominal Wind Speed	12m/s
Minimum Wind Speed	4m/s
Maximum Wind Speed	18m/s
Blade Pitch angle	0

Simulation:

As mentioned in section 5, the A and B combinations use soft starter for network connection. The soft starter is in fact a parallel-inverse connection of two thyristors, whose firing angle decreases by a constant value (α) in each stage until it reaches to zero and are then short circuited by a power switch. The general schematic of a single-phase soft starter is well illustrated in Fig.4.

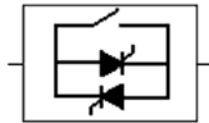


Fig. 4: The general schematic of a single-phase soft starter.

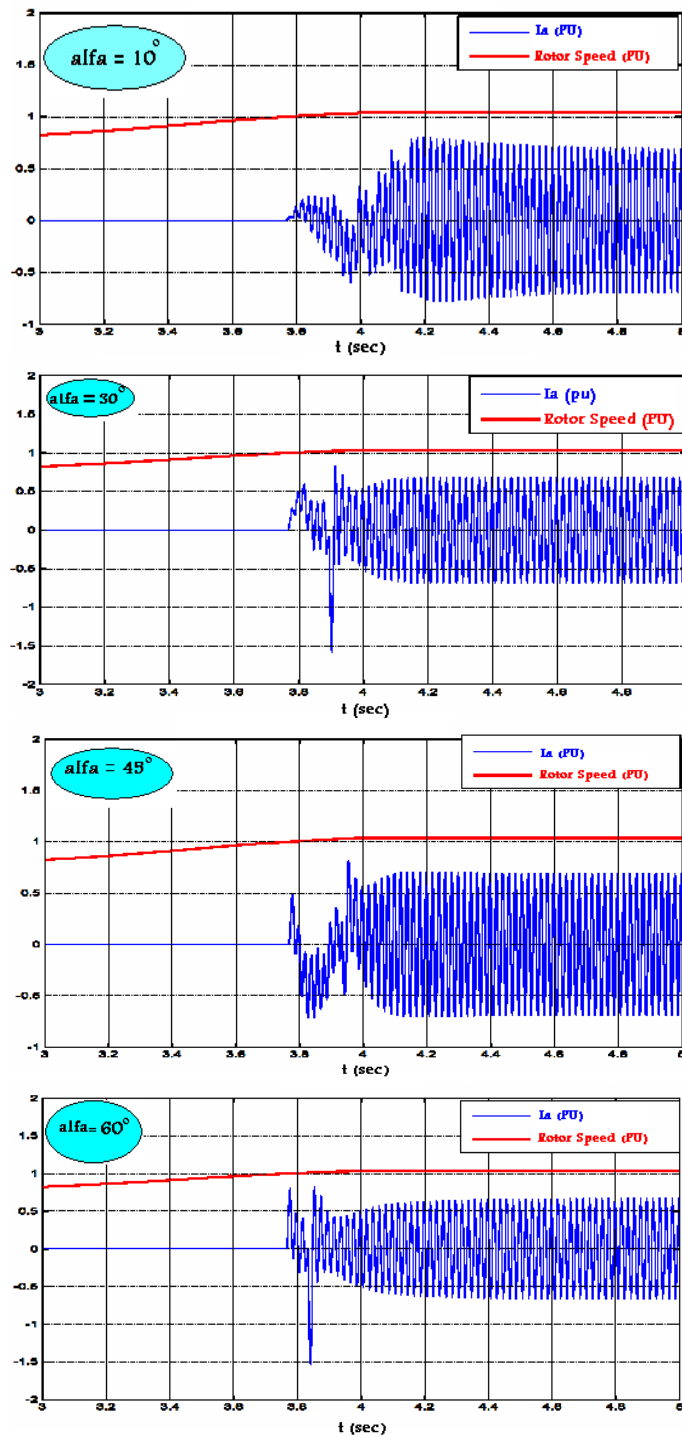
A combination of a turbine-generator connected to an infinitive network, is simulated in order to investigate the effects of α (the thyristors' firing angle difference in two successive cycles) value on wind turbine soft starting. The α value is considered as 10° , 30° , 45° , and 60° , respectively. In one operation mode, the wind turbine is connected to the network holding no soft starter, which is accomplished in synchronous speed. The "a" phase current waveform is considered as the comparison base. Fig. 5 shows the "a" phase current of the induction generator for 30° , 10° , 45° , and 60° α values, respectively. As it is obvious, the a phase current's transient peak and its steady state reaching time increase as the α value increases, which depicts the fact that it is better to connect the wind turbine to the network as soft as possible. Although the transient state last longer in 45° α value in compare with the 30° α value, the current peak value considerably decreases in 45° α value.

In the next stage, the turbine to network connecting speed is varied maintaining α value in 45° and the turbine to network connecting speeds are considered 0.9 p.u. and 1.1 p.u.

Fig.6 shows the "a" phase current waveform of induction generator in different to network connecting speeds. As it is obvious, connection in synchronous speed is the best connecting condition, where the a phase current's transient peak value and the steady state reaching time increase as the synchronous speed is receded.

Finally, the induction generator active and reactive powers in 0.9 p.u, 1 p.u, and 1.1 p.u speeds are shown in Fig. 7. As it is noticed, the peak reactive power absorbance from the network is increased as the synchronous speed is receded. In addition, Q is more absorbed in the speeds more than the synchronous speed in comparison with the sub-synchronous speeds. The active power absorption in order to reach the speeds more than the synchronous speed and to operate in the generation mode increases as the connection speed is lower than the synchronous speed. In the synchronous speed, the P oscillation is observed just in the system connection

moment and the pure received value is almost zero. It is not possible to absorb P in over-synchronous speed connection and the active power is injected to the network from the first moment.



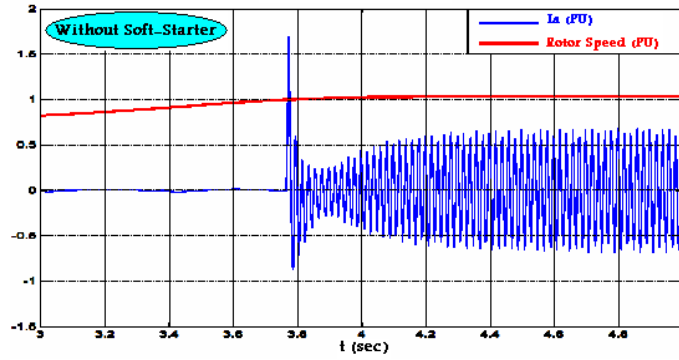


Fig. 5: The “a” phase current of the induction generator for 30° , 10° , 45° , and 60° α values.

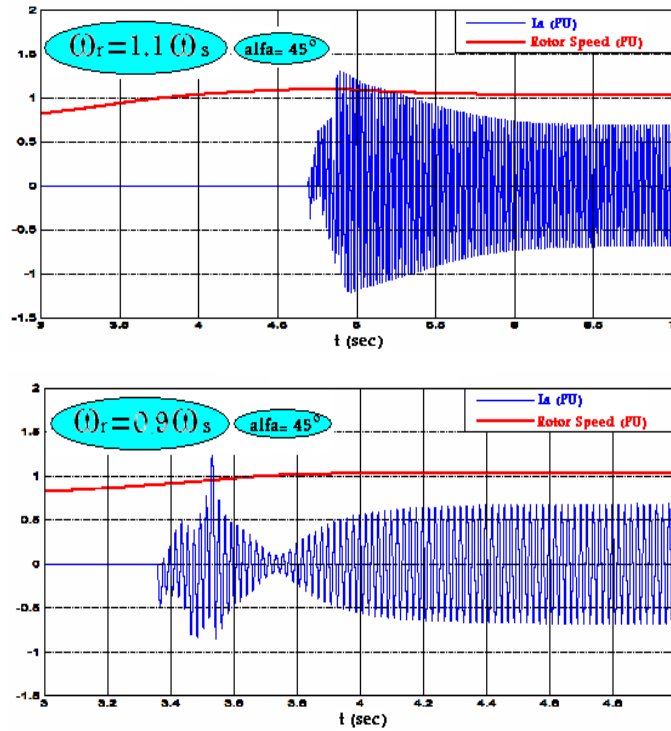
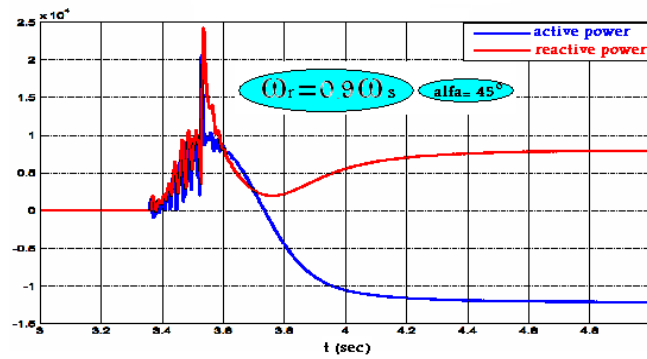


Fig. 6: The “a” phase current waveform of induction generator in different to network connecting speeds.



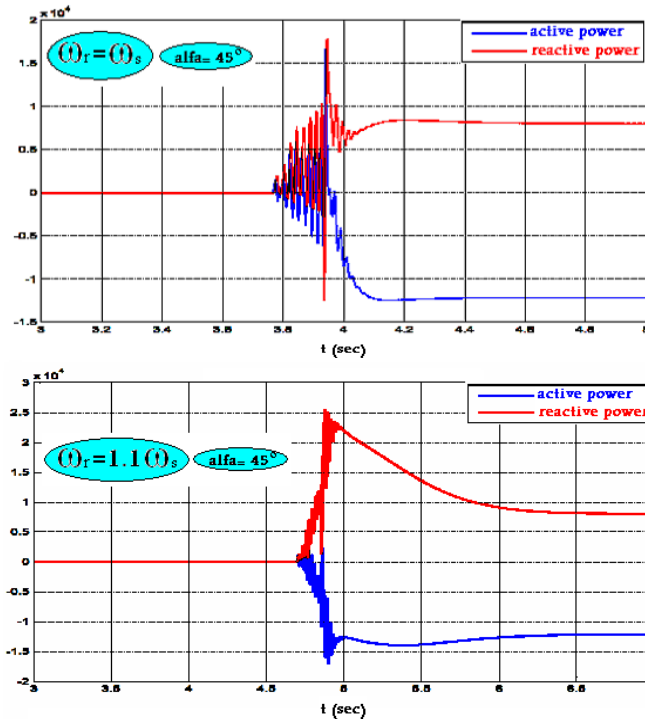


Fig. 7: The induction generator active and reactive powers.

Conclusion:

In this paper, the connection of the constant speed wind turbine to the network through the soft starter is investigated. Soft starter is applied to decrease the starting current value of the wind turbine connected induction generator. The simulation results well show the starting current reduction under soft starter application condition in compare with no soft starter application one. The simulation results also depict that the 45° firing angle is the most appropriate angle for starting. In addition, in synchronous speed system starting leads to the least starting current magnitude.

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