Grid Voltage Dip Impacts on the DFIG Wind Turbine and Its Main AC Contactor Performances

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Abstract—The wind turbines with doubly-fed induction generator are susceptible to grid transients such as voltage dips. Where the DFIGs are connected to the grid by the contactors. The voltage dips affect the AC contactor performance significantly, this leads to the sudden disconnect of the generator from the network, which affects the production behavior of the wind turbines. In this paper, to analyze the impact of voltage dips, the DFIG and its AC Contactor are modelled, where the characteristics of operating limits during voltage dip of the AC contactor has studied, and then its impact on the performance of the DFIG generator. The simulation results depict the impacts of the grid transients on the performance AC contactor and the behavior of the doubly-fed induction generator are also observed.

Index Terms—AC contactor, doubly-fed induction generator, voltage dip, wind turbine.

I. INTRODUCTION

WIND energy is playing a potential role in the establishment of a low-carbon and sustainable energy source. Nowadays, Wind turbines with doubly-fed induction generator are the widely used in varying wind-velocity areas, owing to their ease to control during varying wind speed, the ease to connect to the public grid, the stability of power output, and ease of maintenance [1]. The DFIG is connected to the grid through an AC contactor, which an electromagnetic switch used for connecting the generator to the power system.

Voltage dip is a sudden drop in the grid voltage, which can be caused by a disturbance or faults occurring in the power system. The wind turbines with DFIG are affected by grid disturbance at its point of contact. The grid disturbance also affects the related control devices such as converters, programmable logic controller (PLC) and contactors [2].

The contactor structure consists of an iron core with a magnetic coil, this electromagnetic force moves the contactor armature and its return spring to open and close its contactor contacts. Commonly, the contactor uses the grid voltage to feed its inner coil to operate the mechanism of its switching contacts. Consequently, the contactor is sensitive to the change in the grid voltage, and the voltage dips will affect the contactor performance so it may lose its magnetic force and opens its contacts to disconnect the generator from the Grid [3].

The DFIG generator is an asynchronous machine connected to the grid through a contactor. The stator windings of this generator are connected directly to the grid, while the rotor windings are connected to the grid through a converter system [4]. The DFIG converter consists of an inverter on the rotor and a rectifier on the grid side with a common DC link. The converter is used to control the generator speed, power and power factor, thus allowing the generator to operate within range of variable speeds and to produce power to support the grid. The DFIGs are essentially wound rotor induction machines with the ability to convert the mechanical energy to generate electricity, while the stator will always generate energy to the 3-phase power supply network [5]. The grid-side circuit is connected through a main contactor to the 3-phase power supply, while the rotor circuit is connected to the wind turbine converter through rotor slip rings. Figure 1 shows the doubly-feed induction generator connected to the grid [6].

This paper discusses the model of a wind power system consisting of a doubly-fed induction generator

![Fig. 1. The components of DFIG wind turbines connected to the grid being equipped with its main contactor and connected to the power grid. The model is used to simulate the behaviour and performance of the system during the occurrence of symmetrical voltage dips in the power system. A dynamic model of the contactor is designed](image-url)
to simulate the mechanism of connecting/disconnecting the generator to the grid, in order to study the dynamic behaviour of the AC contactor and its impact on the DFIG wind turbine performance during grid voltage dips. The simulation also includes the modelling of the DFIG wind turbine using the vector control strategy to study the effect of the contactor behaviour during grid voltage dips on the generator performance.

II. The Wind Power System Modelling

A. Principles of Operation

The DFIG wind turbine is a power generating unit using a slip-ring generator to convert wind energy into electrical power. The resulted electricity is supplied to the grid, by connecting to the public grid through a main contactor. It is an electromagnetically-controlled switch which connects/disconnects the generator to/from the public grid according to the wind turbine controls and the generator protection systems. The DFIG is connected to the grid on its two sides, the stator side and the rotor side. The stator is connected directly to the grid via the contactor, whereas the rotor is connected to the grid via the converter. The converter is divided into two sides, rotor side converters (RSC) and grid side converter (GSC). The GSC converts the grid voltage into a DC voltage with a capacitor connected to the DC side of the converter as a DC voltage source, while the RSC inverts and regulates the DC voltage to AC voltage to supply the rotor winding which is connected to the RSC by slip rings and brushes [7]. The wind kinetic energy being captured by the wind turbine is transformed into electrical energy by the DFIG and furthermore transmitted to the grid through the stator and rotor converters. Figure 2 shows the power system components and how the wind turbine is connected to the public power system grid.

![Diagram of DFIG wind turbine connection to the grid](image1)

Fig. 2. The connection of the DFIG wind turbine to the grid through the main contactor

In normal conditions, when the wind turbine reaches its optimal rotation speed, the control system will order the contactor to close the contact switch and to connect the generator to the power system. The converters will furthermore enable the DFIG to operate to generate electricity and power flow into the grid [8].

The control of wind turbine-based DFIG includes two parts, the first part is the wind turbine speed control which controls the rotation speed, torque and pitch angle, whereas the second part is the generator control which consists of the rotor-side converter control and the grid-side converter control. The rotor-side converter control works on the active and reactive power on the stator side, whilst the grid-side converter control regulates the voltage level on the DC bus capacitor by exchanging the active power with the grid. It also has an ability to control the terminal voltage or power factor [9].

B. The Grid Model

The grid model under consideration comprises a 1.5 MW wind turbine being connected to a 25 kV grid via its main AC contactor to a 25/575 kV transformer. The transformer capacity is 2.5 MVA. The contactor is fed on the grid voltage via a 575/240 V auxiliary transformer. The DFIG wind turbine is connected to the distribution system through a busbar and line length of 30 kms and a transformer of 120/25 V to export the power to a 120 kV power system.

C. The AC Contactor Modelling

It is purposed to determine the behavior of the AC contactor during the changes of grid conditions and to simulate its impacts on the generator connected to the grid via the contactor.

The AC contactor is modeled using an electromechanical model used in [10-11]. An AC voltage is applied to a contactor coil, to produce magnetic flux equivalent to the derivative of the flux linkage with respect to time $\frac{d\phi}{dt}$. Besides, it is also related to the number of coil turns $N$.

The terminal voltage equation can be expressed as:

$$u = ri + N \frac{d\phi}{dt} \tag{1}$$

Where $u$ is the system voltage, $\phi$ is the flux linkages produced by the contactor coil, per turn of the exciting coil, $N$ is the number of coil turns, $i$ is the current flowing in the coil, $r$ is the resistance of the coil.

Figure 3 shows the contactor operated by the coil, the spring sets and the contacts. Figure 4 presents the magnetic circuit and its equivalent circuit [12].

![Diagram of AC contactor](image2)

Fig. 3. The structure of contactor

The current passing through the contactor coil generates an electromagnetic force which moves the moving parts of the contactor (armature and contacts). The electromagnetic force between the frame and the contactor armature is defined as follows:

$$F = -\frac{dW}{dx} = -\frac{1}{2} \phi^2 \frac{d\phi}{dx} + f_f \tag{2}$$

Where $W$ is the magnetic energy, $\phi$ is the flux generated on the contactor coil, $R$ is the total magnetic circuit reluctance and $x$ is the air gap distance between the active armature and fixed core. The reluctance can be expressed as:
The AC contactor acts as a magnetizing switch depending on the coil magnetic force and the electrical contact position. The contacts are open/close based on the current supplied to the coil generating the magnetic force to produce mechanical force, which in turn opens and locks the circuit of the DFIG generator. The dynamic behavior of the contactor mechanism is expressed through the use of Newton’s law of motion.

\[ F = -m \frac{d^2x}{dt^2} + D \frac{dx}{dt} + K(x - x_0) \]  

(4)

The contactor model is developed according to the above mentioned equations.

**D. The DFIG Wind Turbine Modelling**

Studying the control process and the behavior of the wind turbine-based DFIG connected to the grid requires the modeling of the system to simplify the different control strategies of the DFIG generator and wind turbine. The induction generator is used for variable speed drives. The stator is directly connected to the grid, while the rotor is fed via a converter which is also connected to the grid, as shown in Fig. 5 [13].

\[ \lambda = \frac{R \omega_m}{v} \]  

(4)

Where \( \lambda \) is the ratio of the tip speed to wind speed, \( R \) is the radius of the wind turbine, \( \omega_m \) is the rotor speed, \( V \) is the wind speed, \( C_p \) is the performance coefficient of the turbine, \( \beta \) is the blade pitch angle.

The performance coefficient is defined as a function of tip speed ratio:

\[ C_p = K_1 \left( \frac{\lambda_2}{\lambda_1} - K_3 - K_4 \beta K_5 - K_6 \right) \left( e^{K_7/\lambda_1} \right) \]  

(5)

With

\[ \frac{1}{\lambda_1} = \frac{1}{\lambda + 0.086} - 0.035 \]  

(6)

The mechanical power in the form of kinetic energy resulted from the wind speed is defined as follows:

\[ P_t = \frac{1}{2} \rho \pi R^2 V^3 C_p \]  

(7)

The mechanical torque is expressed by:

\[ T_m = \frac{1}{2} \rho \pi R^2 V^2 C_l \]  

(8)

In order to study the behavior of the DFIG wind turbine connected to the grid, its dynamic transfer functions must be considered. The vector control of the DFIG is performed in a synchronous dq frame, in which all the rotor quantities are referred to the stator [14]. Thus, the stator and rotor voltages are expressed as follows:

\[ v_{ds} = R_s i_{ds} + \frac{d\phi_{ds}}{dt} - \phi_{qs} \omega_s \]  

(9)

\[ v_{qs} = R_s i_{qs} + \frac{d\phi_{qs}}{dt} + \phi_{ds} \omega_s \]  

(10)

\[ v_{dr} = R_r i_{dr} + \frac{d\phi_{dr}}{dt} - \phi_{qr} (\omega_s - \omega_r) \]  

(11)

\[ v_{qr} = R_r i_{qr} + \frac{d\phi_{qr}}{dt} - \phi_{dr} (\omega_s - \omega_r) \]  

(12)

The flux linkage equations of the stator and rotor can be related to their currents and are expressed as follows:

\[ \phi_{ds} = L_d i_{ds} + M i_{dr} \]  

(13)

\[ \phi_{qs} = L_q i_{qs} + M i_{qr} \]  

(14)

\[ \phi_{dr} = L_r i_{dr} + M i_{ds} \]  

(15)

\[ \phi_{qr} = L_r i_{qr} + M i_{qs} \]  

(16)

The electromagnetic torque \( T_{em} \) can be written as a function of stator fluxes and rotor currents:

\[ T_{em} = p \sum_{r} \left( \phi_{dr} i_{qs} - \phi_{qr} i_{ds} \right) \]  

(17)

Under the two-phase coordinate system, the active and reactive powers of the generator are written as following:

\[ P_s = V_{ds} i_{ds} + V_{qs} i_{qs} \]  

(18)

\[ Q_s = V_{qs} i_{ds} + V_{ds} i_{qs} \]  

(19)

In normal operation of the DFIG, in order to transform the mechanical energy into electrical power, the electromagnetic torque of the generator must be controlled by the stator currents or rotor currents depending on the control strategy, which is clearly shown in Eq. 17, but these currents are generated as a function of grid voltage shown in Eq. 9 and Eq. 10. In this case, the purpose of the grid side converter is to control and maintain the input voltage through converter control strategies to be a constant value during the normal operating conditions.
E. Voltage Dip

Voltage dip is defined as a short duration of reduction in RMS voltage which happens when the grid voltage suddenly decreases between 10 and 90 percent of its nominal value for a one-half cycle to one minute [15]. Describing the magnitude of a voltage dip is often difficult as according to IEC standard, the voltage dip should be specified as the remaining voltage of nominal [16]. Voltage dip affects many electrical devices, including the PLCs control units, contactors, relays, generators, and converters. It sometimes leads to the instability on the grid which may cause block out of part of the power system [17]. Voltage dip is, therefore, a transient in the voltage amplitude. It is caused by sudden increase in loads or system faults such as phase to phase or phase to ground short circuits.

Since the voltage dips may affect the generator parts, the auxiliary controls such the relays and main contractors are also affected by this voltage fluctuation. The electromagnetic AC contactor is affected by the grid voltage disturbance, which may drop out when the voltage is dipped for a period or more than one cycle, which may affect the performance of the generator and cause disconnection from the public grid.

III. SIMULATION RESULTS

The DFIG wind turbine connected to the grid via its main contactor has been simulated to study its behaviour during normal and transient fault grid conditions. The simulation is carried out by modifying the DFIG wind turbine system being detailed in [18]. The model includes a power source, transformer, overhead line busbar and also an AC contactor connecting the DFIG-based wind turbine with a complete representation of power electronic converters.

In the simulation, the DFIG was subjected to a severe voltage dip of about 60%, 40% and 20% during 0.15 second. The AC contactor model was used to investigate its dynamic performance as discussed previously. The vector control model was used for controlling both the RSC and GSC of the DFIG wind turbine. It was assumed that the DFIG has been operating at normal conditions while the contactor was in close contacts to connect the generator to the grid to start its normal operation and to produce its nominal active power at its steady-state condition. In addition, the wind speed is assumed to be constant during the simulation time.

A. The System Behaviour under Normal Grid Condition

During the normal operation of the system, as shown in Fig. 6, the grid voltage which represents the system voltage on the wind turbine was stable at 1 p.u., whereas the grid current was fluctuating normally at start-up time until 0.1 seconds, then being stable at 0.15 p.u.

Figure 7 describes the contactor status during normal operation. The grid voltage causes the magnetic coil to produce a magnetic flux, which generates magnetic force which changes the contactor’s contacts status

![Fig. 6. Simulation results of grid voltage and current under normal grid operating condition](image)

(On/Off) to connect the generator to the grid. Figure 7 also shows the auxiliary voltage of the contactor coil reaching a constant value at 240 V.

Also shown in Fig. 7, the magnetic force produced by the contactor coil was of average value around 10N, which was higher than the return spring force. Thus, the contactor closed its contacts and the generator was connected to the grid. The contactor coil flux and the contactor status are also shown in Fig. 7. The close contacts condition is indicated by the status value “1” in Fig. 7, meaning that the contactor closed its contacts to connect the DFIG to the grid under its normal operating condition.

![Fig. 7. Simulation results of contactor condition at normal operation of the DFIG connected to the grid, indicating the contactor voltage, the contactor coil flux, the contactor magnetic force, and the states of contactor](image)

During the simulation time, when the generator was connected to the grid via its contactor, the stator voltage was constant, stable at 1 p.u. as shown in Fig. 8. Figure 8 indicates that the stator current fluctuates between 3 to 1 p.u for 0.1 second during startup, before becoming stable at 0.8 p.u. The rotor voltage value was constant at 1 p.u. The rotor currents of the DFIG fluctuate between 3 to 1 p.u for 0.1 second during the startup before becoming stable at 0.8 p.u.

Figure 9 shows the simulation results of the normal status of DFIG under normal grid condition, including the active power, reactive power, the DC voltage, and the electrical torque.

As shown, along with the simulation duration the system reached the generated power near its nominal value at its steady-state condition. The active power has
been extracted from the DFIG wind turbine and stable to 1.5 MW after 0.28 seconds from the simulation time beginning. It is noted that the generated active power was injected into the grid and the reactive power was controlled to zero as remarked in Fig. 9. It is also shown that the DC bus voltage has been regulated to 1100 V at the steady-state condition. As shown in Fig. 9 the electrical torque was also regulated at 0.2 p.u.

In general it can be observed that when both rotor and stator converter sides of the DFIG generator are connected to the power system, in normal condition the generator will produce transient power during starting, which become stable after reaching the steady-state condition.

A voltage drop on the grid needs to be created during the simulation to observe the effect of the grid voltage dip on the grid-connected DFIG wind turbine system.

B. The System Behaviour under Grid Voltage Dip Condition

The main drawback of the DFIG is its sensitivity to grid voltage disturbances since the generator is directly connected to the grid. The grid disturbance will cause a stator perturbation and affect the connected electromagnetic devices. The disturbance will be transferred to the rotor windings, and consequently to the rotor-side converter. To study these effects, a voltage dip occurrence has been considered during the simulation. The voltage dip was assumed to happen at the instant time 0.3 second and was remaining during 150 seconds.

a. Simulation results of wind turbine system under 60% of grid voltage dip condition

With the assumption of the fault occurrence in a form of grid voltage decrease to 60%, the simulation results to analyse its impact on the grid and DFIG wind turbine components are given in Fig. 10. As seen, when the fault occurred at t=0.3 s, the grid voltage value decreased to around 0.6 p.u. It can also be seen that the current transient change is observable at the moment the voltage value changes, before reaching its steady-state value. The first transient with a current increase up to 0.3 p.u. started at 0.3 second when the voltage dip began. It was continuously decreasing towards its steady-state value at around 0.2 p.u. before the next transient increase happened again when the voltage dip disappeared at around 0.45 second.

The impact of 60% of grid voltage dip on the main contactor is described using Fig. 11. The contactor voltage decreased to reach 180 V during the voltage dip, as shown in Fig. 11. This disturbance leads to the weakening of the electromagnetic force of the contactor coils, even if the coil magnetic force is still greater than the armature return spring force. Consequently, as shown in the last picture of Fig. 11, the contactor was still in the close position and keeping the generator connected to the grid.

Figure 12 illustrates the simulation results of the grid-connected DFIG wind turbine system under 60% of grid voltage dip condition, especially on the stator voltage, stator current, rotor voltage, and the rotor current.

As seen, when the fault occurs, the stator voltage decreased to 0.6 p.u., whereas the stator current experienced a transient increased up to 1.1 p.u, which was occurring again at the time of the fault removal at 0.45s. The rotor voltage also experienced a certain disturbance in the form of more pronounced peak value variation, between 0.7 to 0.72 p.u. The associated rotor current values are also given in Fig.12. The peak rotor current increased up to 1.1 p.u when the voltage dip appeared and started to recover its normal value after another transient increase when the dip disappeared.

The simulation results of the 60% voltage dip impacts on the generated power and electromechanical torque are given in Fig. 13. It also includes the condition on the DC link of the converter.
It shows that during the voltage dip, the active power dropped to 1MW while the generator started to absorb a reactive power from the grid to reach 0.8 MVAR. The system started to recover its normal condition when the voltage dip disappeared.

A bit of distortion in the DC-link voltage during the grid disturbance can also be observed in Fig. 13. It indicates an acceptable slight influence on the converter during this type of grid fault. The impact on the mechanical parts of the system can be seen from the electromechanical torque condition. As seen, it is disturbed during the occurrence of the voltage dip. However, the torque distortion was still acceptable and did not affect the mechanical behaviour of the wind turbine.

b. Simulation results of wind turbine system under 40% of grid voltage dip condition

The impacts of 40% grid voltage dip on the behaviour of the grid-connected DFIG wind turbine system are presented in Fig. 14 - Fig. 17.

Figure 14 indicates the impacts of 40% grid voltage dip on the grid voltage and current. Being compared to the impacts of 60% voltage dip shown in Fig. 10, it can be observed that transient increase of grid current at the occurrence of the voltage dip was followed with a sudden loss of current. This because the voltage disturbance produced the disconnection of the generator from the grid by the main contactor. When the grid voltage recovered its normal value, the generator reconnected and the grid current started to reappear through the starting transient before reaching its new steady-state condition.

Figure 15 indicates the impacts of 40% grid voltage dip on the main contactor. As seen, the contactor voltage decreased to around 100V at the beginning of dip occurrence at 0.3 second. It causes a sharp drop in the electromagnetic force of the coils, leading to the moment of the contacts return spring force which is responsible for the opening of the contactor contacts, stronger than the magnetic force generated by the coil operating voltage during the voltage dip. This is due to the decrease of the magnetic field generated by the contactor coil as apparent in Fig. 15, which leads to a change in the contact position of the contactor to the opening position during the fault condition.

As a result of the voltage dip impacts on the contactor, there is a disturbance in the performance of the generator due to its disconnection from the grid, causing the voltage on the stator side of the generator to be zero. Fig. 16 shows the effect of voltage drop and the result of disconnecting the network voltage from the generator during the grid transient fault.

As seen in Fig. 16, the stator voltage disturbance during the fault period faded gradually as a result of the DFIG stator disconnection from the grid, because of the contactor behaviour at 40% grid voltage dip explained in Fig. 15. Similarly, the stator current indicates more significant deterioration, being compared to that in the case of 60% of voltage dip. As shown, the current overshot to 2 p.u., being followed with fluctuation between 0 and 0.8 p.u. until the fault disappeared at 0.45s, at the time the generator connected to the grid again through the contactor. The current overshot to 3 p.u. appeared again at the moment of reconnection to the grid, then attenuating to its steady-state value.

Figure 17 indicates the impact of 40% voltage dip on the generated power and the mechanical parts of the system. Figure 17 shows the presence of DC-link voltage on the rotor-side converter with zero value at the time the rotor voltage faded away during the end of the voltage dip period, as seen in Fig.16.

Fig. 13. The impacts of 60% of grid voltage dip on the generated power and mechanical parts of the grid-connected DFIG wind turbine

Fig. 14. Simulation results of grid voltage and current during the occurrence of 40% of grid voltage dip

Fig. 15. The impacts of 40% of grid voltage dip on the main contactor of the DFIG wind turbine, indicating the contactor voltage, the coil flux value, the contactor magnetic force, and the state of contactor

Fig. 16. The impacts of 40% of grid voltage dip on the stator and rotor voltage and current of the grid-connected DFIG wind turbine
The voltage dip disturbance affected the generator performance and power generation stability. This condition is incompatible with Fault-Ride Through code which requires the DFIG wind turbines to stay connected to the grid during the grid transients such as the voltage dip.

REFERENCES


IV. CONCLUSIONS

This paper deals with voltage dip effects on the performance of DFIG wind turbine connected to the grid via an AC contactor. During normal operation, the wind turbine controls order the contactor to close its contacts to connect the generator to the grid to start its normal operating condition and power generation process, where AC contactor uses the grid voltage to magnetizing its armature to close its contacts then connecting the DFIG to the public network to feed their stator and rotor sides by grid voltage to begin the power production. Therefore, the study showed a large impact on the contactor mechanism during grid voltage dips, which returned negatively on the generator due to the complete disconnect from the grid. This paper succeeds in studying the effects of grid voltage dips on both the DFIG wind turbine and its AC contactor. The contactor mechanism DFIG has been simulated, and the impacts of the AC contactor on the performance of generator during the voltage dips has been analysed. The results show that the voltage dips below 60% of grid voltage significantly affect the performance of the AC contactor, which affects the behaviour of the DFIG.