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THE FINITE SET MODEL PREDICTIVE CONTROL OF DOUBLY FED INDUCTION GENERATOR SUBJECTED TO UNBALANCED GRID VOLTAGE DEFECTS

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ABSTRACT

This paper proposes a finite set model predictive control of doubly fed induction generator under unbalanced grid voltage conditions. The generation of sufficient power which equals the load demand and grid voltage stability is the major concerns that are to be addressed during the last decade. When the high capacity wind power generation is synchronized with the power grid, several problems in the dynamic behaviour of the power system are raised. During grid faults the transients are observed in the power system; when transients, occur the low voltage ride through is the major concern for the wind turbine to be in stable state. During this period the wind turbines inject harsh distorted currents in to the power system due to the unbalanced grid voltage conditions. The doubly fed induction generators are most commonly used in the wind turbine due to the presence of low voltage ride through (LVRT) and high voltage ride through (HVRT) capabilities. This paper provides a complete study on the LVRT and HVRT capabilities of DFIG based wind turbines. It also analyses dynamic behaviour and transient characteristics of DFIG during symmetrical and asymmetrical grid voltage swell and dip conditions. The effectiveness of the theoretical analysis is verified by using MATLAB/Simulink.

KEYWORDS: *DFIG, Grid Voltage Failure, LVRT Control, Wind Power Generation*

Article History

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INTRODUCTION

Wind power generation is the most developing renewable energy source in the world, now-a-days 83 countries around the world are using wind mills to generate power and supply the grid [1, 2]. The cost of doubly fed induction generator (DFIG) is less and also it requires converter at 30% of generator capacity. Different control techniques are used for the doubly fed induction generator (DFIG) under unbalanced grid voltage condition based on vector control or field oriented control [3, 4].

This paper proposes the LVRT and HVRT strategy of doubly fed induction generator (DFIG) under control of grid voltage dip and grid voltage swell conditions. The fault control ability of wind power specially including low voltage ride through(LVRT) and high voltage ride through(HVRT) is done by using doubly fed induction generator(DFIG) [5].the voltage dips are mainly occurs due to earth faults and short circuit in the grid. When a short circuit occurs then it provides LVRT control strategy. The wind turbine is not designed to achieve these requirements and disconnected from the grid during power system disturbance [6].The voltage swell occurs at point of common coupling (PCC) when the wind turbine is disconnected from the grid. To overcome this difficulty a STATCOM reactive power compensation device is used to absorb excess reactive power and attain the voltage control [7].

To shorten the control complexity, direct torque and power control can be used. The algorithm of direct torque control (DTC) is most simple technique. direct torque control (DTC) produces high level of torque ripple during steady state period [8].To overcome this draw back direct torque control space vector modulation (DTC-SVM) control can be used. DTC-SVM is used to improve the steady state and dynamic response. It offers reduces phase current distortion and good torque response [9].

Model predictive control strategies can be used for the control of converter. In case of continuous control set model predictive control (CCS-MPC) technique a modulator can be bring about switching states based on the predictive control continuous output [10].

This paper provides finite set model predictive control (FC-MPC) technique can be used to optimize the control of inverters. It also improves the output voltage quality of inverters. The MPC also used to LVRT control to improve the transient stability of the power system [11].

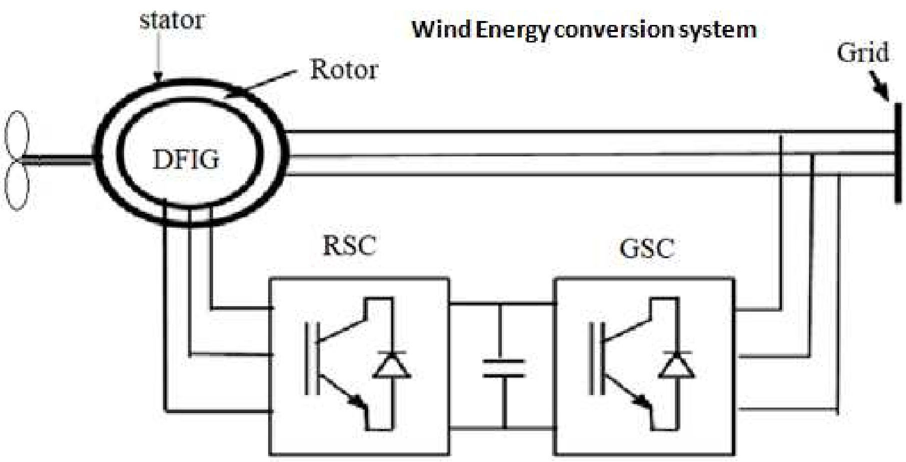


Figure 1: Schematic Connection of DFIG to Grid.

In DFIG the back-to-back converter is used as shown in Fig1. The stator windings of the DFIG are connected directly to the power grid. While the rotor windings are coupled to the converter. In this configuration both the frequency and the current amplitude in the rotor windings can be freely regulated. Besides it can realize soft start for the wind turbine and provide the grid fault ride-through ability. It can also reduce the mechanical stress to the wind turbine

There is a best control technique that was developed to obtain a fast dynamic response that is a predictive current control method based on the theoretical calculation [12]. The experimental results from MATLAB/Simulink were evaluated in this paper by short circuiting of rotor side converter by providing crowbar device [13]. The changing factors of DFIG are influenced by the power grid's voltage dip and swell which occurs due to the change in wind speed. Here we compare and analyse the difference between the two faults [14].

MATHEMATICAL MODELLING OF DFIG

The demonstration model of the DFIG is shown in Fig.1, considering the generator's variables in the alpha beta reference frame. The stator voltage and rotor voltage and flux equations can be written as

$V_s = R_s\, i_s + p\, \psi_s$ (1)

$V_r = R_s\, i_r + p\, \psi_r - j\, \omega_r \psi_r$ (2)

$\psi_s = L_s\, i_s + L_m\, i_r$ (3)

$\psi_r = L_m\, i_s + L_r\, i_r$ (4)

$Te=3/2\, pIm\, \{\Psi_s{}^*I_s\}$ (5)

$S = P + j\, Q = 1.5\, I_s{}^* v_s$ (6)

Where the variables are defined as follows:

- $V_{s,} V_{r\,=}$ stator voltage and rotor voltage vectors
- I_s, $I_{r\,=}$ stator current and rotor current vectors
- $\Psi_{s,} \Psi_{r\,=}$ stator flux and rotor flux vectors
- L_s, L_r= stator self inductance and rotor self inductance
- L_m = magnetising inductance
- R_s, R_r= stator resistance and rotor resistance
- T_e = electromagnetic torque
- P,Q= stator active power and stator reactive power
- $\omega_{s,}$ ω_r=synchronous and rotor electrical speed
- ρ = d/dt
- P= no.of pole pairs
- *= complex conjugate operation

The active and reactive power at the stator and rotor windings can be calculated as follows:

$P_s = 3/2\, (vs\alpha\ is\alpha + vs\beta\ is\beta)$ (7)

$Q_s = 3/2\, (vs\beta\ is\alpha - vs\alpha\ is\beta)$ (8)

$P_r = 3/2\, (vr\alpha\ ir\alpha + vr\beta\ ir\beta)$ (9)

$Q_r = 3/2 (vr\beta\ ir\alpha - vr\alpha\ ir\beta)$ (10)

The voltage drops at time t=0 from its initial value V_{pre} to its final value V_{fault}.

$V_s{}^s(t<0)= V_{pre}\, e^{\,j\omega st}$ (11)

$V_s{}^s(t>0)= V_{fault}\, e^{\,j\omega st}$ (12)

In actual systems the voltage drops with a particular derivative which depends on the grid and the characteristics of the fault that has caused the voltage dip.

DFIG MODEL PREDICTIVE POWER CONTROL

The model predictive control is also used to DFIG's wind power system is shown in Fig 2. It is a simple technique. This model predictive control (MPC) predicts behaviour of the system in future. By using MPC we minimize the cost function and admirable steady state response can be obtained. The stator resistance is neglected (R_s=0). The relationship between the stator voltage and flux in steady state can be concluded from (1) as

$$V\,s = j\omega_1\Psi_s \tag{13}$$

From (3) and (4), the stator current can be expressed by stator and rotor flux

$$I_s = \lambda\,(L_r\,\Psi_s - L_m\,\Psi_r) \tag{14}$$

Where λ=1-L_m^2/ (L_s L_r).

By substituting (13) and (14) into (6), the stator output apparent power can be calculated using Ψs and Ψr so that

$$S = j3/2\ \lambda\omega_1\,[L_r\,|\Psi|^2 - L_m\,(\Psi_r^*\ \Psi_s)]$$

Thepower derivatives can be approximated to

$$dp/dt = 3/2\ \omega_1\,\lambda L_m\,[\mathrm{Im}\{V_r^*\Psi_s\} + \omega_s\,\mathrm{Re}\{\Psi_s\,\Psi_r*\}] = f_p \tag{16}$$

$$dq\,/\,dt = -3/2\omega_1\lambda L_m\,[R_e\,\{V_r^*\Psi_s\} - \omega_s\,\mathrm{Im}\,\{\Psi_s\,\Psi_r\}] = f_q \tag{17}$$

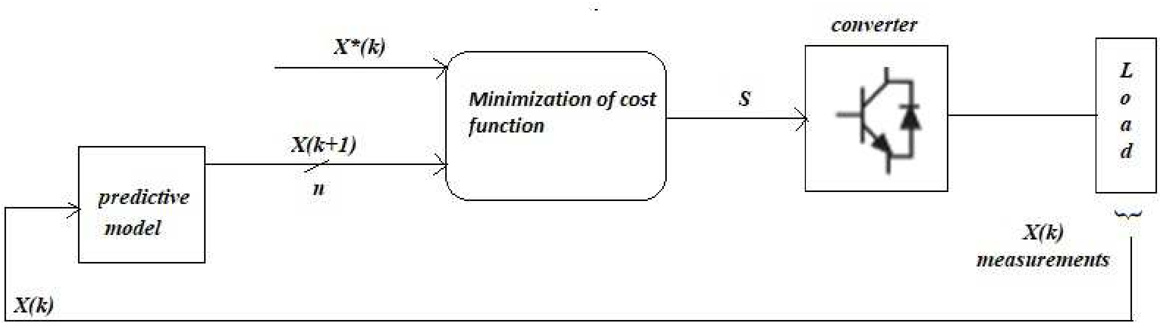


Figure 2: Block Diagram of MPC for Power Converter.

The MPC scheme was applied to power converters and drives is conferred in Fig 2. It represents the topology of converter or grid or any other active or passive load. In this method measured changeable x(k) are used to compute predictions x (k+1) of the controlled variables for each one of the n feasible actuations, i.e., currents or voltages, switching states and these predictions are analysed using a cost function which takes the reference values x∗(k) and constraints, and hence optimal actuation S is picked and enforced in the converter.

STATOR TRANSIENT FLUX ANALYSIS OF GRID VOLTAGE DIP

Assume if the system is stable before t_0, the stator voltage can be expressed as

$$Vs = U\,e^{j\,\omega 1\,t}\ (t < t0) \tag{18}$$

Where

U = the amplitude of the stator

W_1= stator synchronous angular velocity

If the symmetrical grid voltage occurs at t0, set the amplitude of grid voltage is P if P < 0 the system voltage drop occurs. When P > 0 the system voltage swell occurs.

Stator voltage can be written as follows

$$Vs=(1 + P)\ U\ e^{j\omega_1 t}\ (t > t_0) \quad (19)$$

The corresponding stator flux before and after the dip appearance

$$\Psi_s = V_{pre}\ e^{j\omega st}(t < 0)\ /j\omega s \quad (20)$$

$$\Psi s = \Psi 0\ e^{-t\ /\ \Gamma s}(t > 0) \quad (21)$$

Where

Ψ_0= initial value of flux for (t=0)

$\Gamma_s = L_s / R_s$ = stator time constant

During grid voltage fault the stator flux linkage can be gradually transitions from one study state to another because flux can't be mutated. Assume rotor is open during short circuit condition the voltage is zero (V=0).the machine demagnetized there is no flux no EMF induce in rotor winding.

Substitute stator flux equation in to stator voltage equation

$$d/dt\ \Psi s = V_s - R_s / L_s\ \Psi_s \quad (22)$$

By solving above equation we get

$$\Psi_s = (1+P)\ U\ e^{j\omega_1 t} + \Psi_{no} e^{-t\ /\ \Gamma s}\ /j\omega_1 \quad (23)$$

Where

Ψ_{no} = constant (rated flux condition)

$\Gamma_s = R_s / L_s$

It analyses the flux doesn't rotate during dip it is fixed with rotor. The flux which is rotates at grid frequency before the dip and it freezes during the dip. Its amplitude decays gradually from its initial value to zero with stator time constant.

Assuming that the grid fault occurs at time t_0 =0

Both (22) and (23) equations can be written as

$$\Psi_s = (1+P)\ U\ e^{j\omega_1 t} / j\omega_1 -\ PU\ e^{t / \Gamma s} / j\omega_1 \quad (24)$$

ELECTROMAGNETIC FORCE INDUCED IN THE ROTOR DURING GRID VOLTAGE DIP

The electromagnetic force induced in rotor windings during grid disturbances the grid voltage fails. A small difference between the stator and rotor flux due to leakage inductances.

By using equations (18) and (19) the relation can be expressed as

$$\Psi_r = L_m \Psi_s / L_s + \sigma L_r i_r \quad (25)$$

Where

$\sigma = 1 - L_m^2/L_sL_r$ is leakage co-efficient

Substituting (25) into rotor voltage equation (2) it can be written as

$$V_r = L_m \Psi_r/L_s(d/dt - j\omega_r) + [Rr + \sigma L_r (d/dt - j\omega_r)]\, i_r \quad (26)$$

In the equation (26) first term is the EMF generated by the stator flux on the rotor loop, denoted by v_{ro}, it is the rotor open circuit voltage and the second term is the rotor loop impedance drop.

The electromotive force induced on the rotor loop by the stator flux steady state and transient components are denoted by the e_{rf} and e_{rn} respectively, and the relationship with the rotor open circuit voltage can be expressed as,

$$Vro = e_{rf} + e_{rn} \quad (27)$$

Calculatedby (23) and (26) are available

$$e_{rf} = L_m/L_s V_{fault} e^{\omega r\, t} s$$

$$e_{rn} = -L_m /L_s (1 + r_s + j\omega_r) \Psi_{sn} \quad (28)$$

Where, $s = (\omega_1 - \omega_r)/\omega_1$ is the slip ratio

Neglecting the small term $1/r_s$, there are

$$e_{rn} = -j\, \omega_r (L_m / L_s) \Psi_{sm} \quad (29)$$

Therefore, the rotor open circuit voltage in co-ordinate system can be written as

$$v_{ro} = L_m/L_s U[(1+p)se^{j\omega st} + (1-s)pe^{-j\omega r\, t} e^{-t/rs}] \quad (30)$$

From the equation (30), it can be seen that, after the grid fault the rotor steady state amplitude of open circuit voltage is 1+p times that before the grid fault.

STATOR CURRENT OF GRID VOLTAGE DIP

There is no current in rotor, before and during the dip the stator current can be written as

$$I_s = \Psi_s / L_s\ (t < 0) = v_{pre}\, e^{j\omega st} / j\omega L_s$$

$$I_s = \Psi_s/L_s\ (t > 0) = \Psi_0\, e^{-t/rs} / L_s \quad (31)$$

The space vectors of currents stops rotating during dip which implies the circulation of DC currents in stator reference frame. These currents are not constant as they decay exponentially with the same dynamics as the flux.

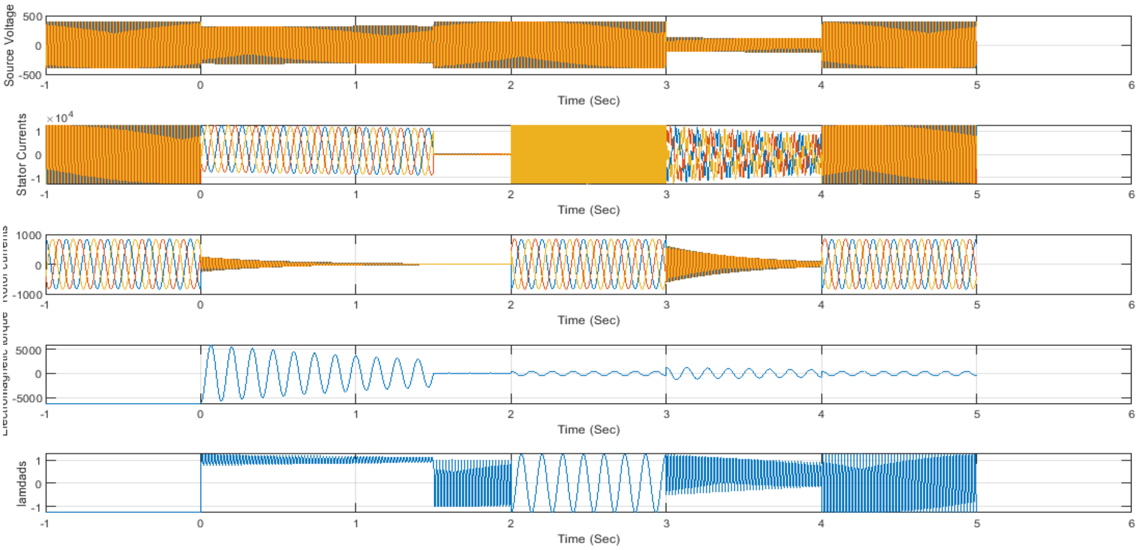
ROTOR CURRENT OF GRID VOLTAGE DIP

The doubly fed induction generator is operating normally, the influence of rotor current can be considered .the equation (26) can be written as stator co-ordinate into synchronous rotating co-ordinate system.

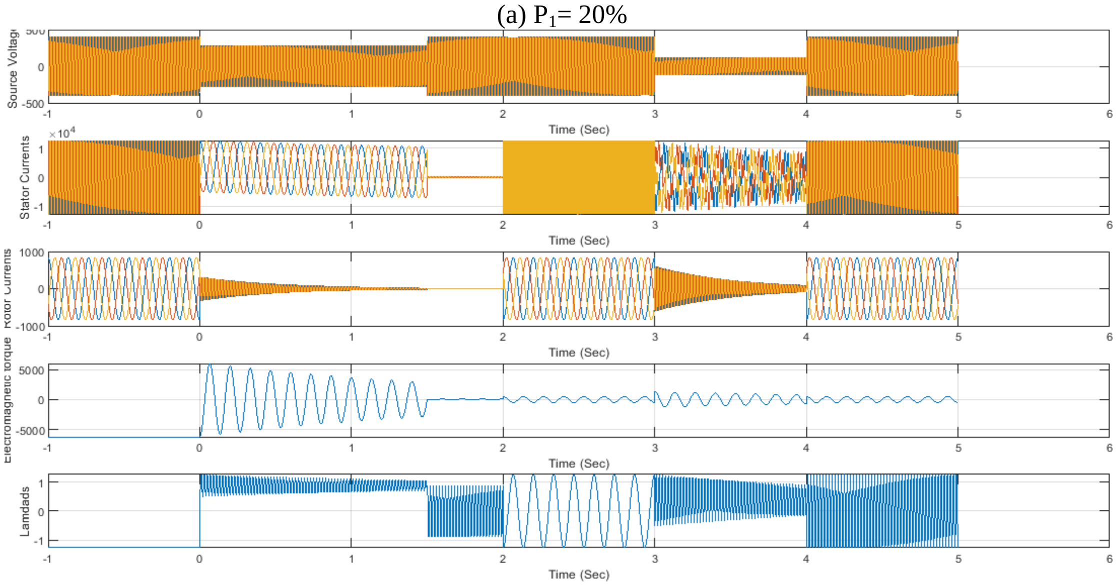
$$\sigma L_r\, di_{r,dq}/dt + (R_r + j\omega \sigma L_r)\, i_{r,dq} = \mathbf{v}_{r,dq} - \mathbf{v}_{ro,dq}$$

SIMULATION RESULTS

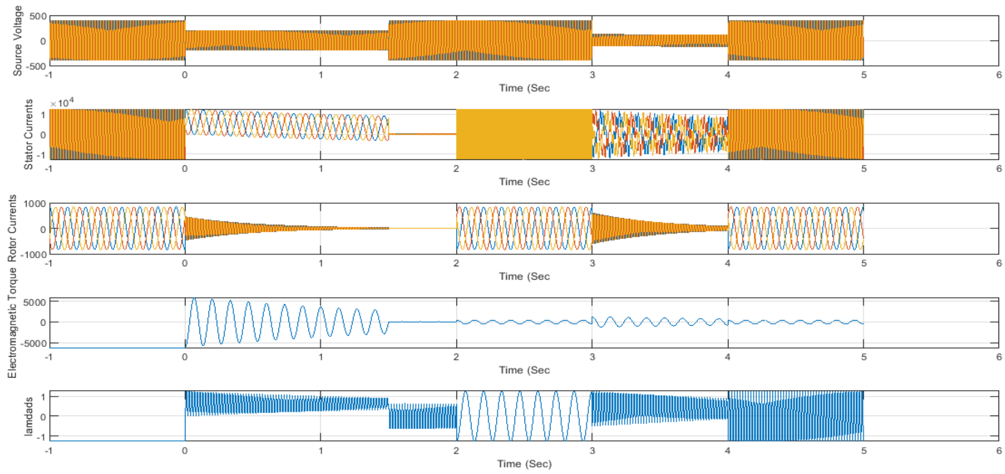
The simulation results are constructed based on MATLAB/SIMULINK to verify the mathematical model of DFIG under unbalanced grid voltage conditions. For simulation the rating of the DFIG is taken as 1.5MW. The performance of DFIG under the second fault occurs at time t=500ms and they are shown in the appendix. The level of voltage dip at P1=50% and the rotor speed of n_r=1725 rpm and the grid fault angle at the first fault occurs at 40^0.The level of voltage dips for the first grid fault P_1 at 80%,50%,30%,20% are shown in fig.(3). The rotor current, stator current and electromagnetic torque of the DFIG with different P_1 are shown in fig.3 (a), (b),(c) and(d). The first grid fault of 80%,50%, 30%, 20% respectively is reduced by using crowbar technique. The maximum rotor current I_{rm}, stator current I_{sm} and maximum torque fluctuations T_{em} is decreased with the decrease of $P_{1.}$as shown in fig (3).



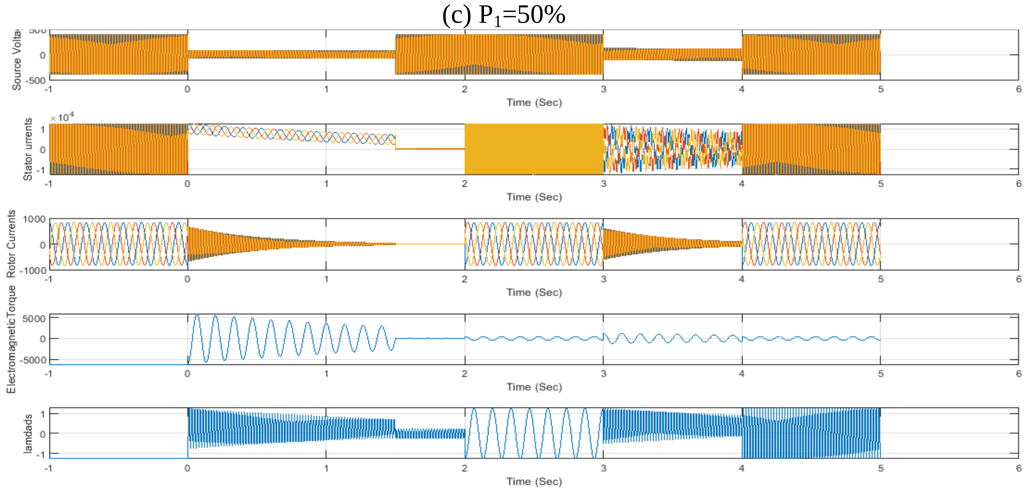
(a) P_1= 20%



(b) P_1=30%



(c) P_1=50%



(d) P_1= 80%

Figure 3: Simulated Performance of DFIG with Different Voltage Dips Level of the First and Second Grid Faults P_1, P_2, (a) P1=20% (b) P1=30% (c) P1=50% and (d) P1=80%.

The level of the voltage dip for the first and second faults at 20%, 30%, 50% and80% are as shown in the fig.(3), The stator resistance (R_s) of small-scale DFIG is high .during vector control stator time constant r_{re} is smaller. As a result, the influence of voltage recovery of the first voltage dip on the second voltage dip will be smaller if the duration between two faults ($p_1$andp_2) is fixed. So, with the same situation the maximum rotor current I_{rm}, stator current I_{sm} and torque fluctuations T_{em} on the second fault will be smaller. In case of large scale DFIG the influence of voltage recovery of first voltage dip on the second voltage dip will be larger. The first grid fault p1 is reduced to 50% and 20% respectively, the maximum rotor current I_{rm}, the maximum stator current I_{sm} and the maximum torque fluctuations T_{em} is decreased with the decrease of P_1.

CONCLUSIONS

This paper presented the dynamic behaviour of doubly fed induction generator under grid voltage dip condition. When the sudden rise of grid voltage is occurred it is necessary for the DFIG to withstand the low voltage ride through capability of equipment at the grid side converter. It can be done with the help of crowbar and vector control methods. The rise in voltage causes over modulation of converter which develops in suppressible current by accommodating dc bus voltage and governs the system side to absorb reactive power to reduce the voltage at AC side terminal can be improved. By proposing FCS-MPC strategy the output voltage quality of inverter has improved.

REFERENCES

1. *J. Hu, J. Zhu and D. G. Dorrell, "Model-predictive direct power control of doubly-fed induction generators under unbalanced grid voltage conditions in wind energy applications," in IET Renewable Power Generation, Vol. 8, No. 6, pp. 687-695, August 2014.*
2. *K. Kerrouche, A. Mezouar, Kh. Belgacem, Decoupled Control of Doubly Fed Induction Generator by Vector Control for Wind Energy Conversion System, Energy Procedia, Volume 42,2013,Pages 239-248,ISSN 1876-6102.*
3. *Y. Deng, Z. Xing and Q. Zhang, "Analysis of electromagnetic transient characteristics of doubly-fed induction generator under grid voltage swell," in CPSS Transactions on Power Electronics and Applications, Vol. 3, No. 2, pp. 111-118, June 2018.*
4. *F. Poitiers, T. Bouaouiche, M. Machmoum, Advanced control of a doubly-fed induction generator for wind energy conversion, Electric Power Systems Research, Volume 79, Issue 7,2009,Pages 1085-1096,ISSN 0378-7796.*
5. *L. Niu, X. Wang, L. Wu, F. Yan and M. Xu, "Review of low voltage ride-through technology of doubly-fed induction generator," in The Journal of Engineering, Vol. 2019, No. 16, pp. 3106-3108, 3 2019.*
6. *A. Rini Ann Jerin, Palanisamy Kaliannan, Umashankar Subramaniam, Improved fault ride through capability of DFIG based wind turbines using synchronous reference frame control based dynamic voltage restorer ,ISA Transactions, Volume 70,2017,Pages 465-474,ISSN 0019-0578.*
7. *Z. Le, W. Xueguang, K. Longze, L. Dong, L. Fangyuan and H. Mingxiao, "Control strategy of doubly-fed induction generator during the grid voltage swell," in The Journal of Engineering, Vol. 2019, No. 16, pp. 1807-1811, 3 2019.*
8. *T. Vinay Kumar and S. Srinivasa Rao, "Direct torque control method for induction motor drives based on modified amplitude and angle decoupled control of stator flux," 2010 Joint International Conference on Power Electronics, Drives and Energy Systems & 2010 Power India, New Delhi, 2010, pp. 1-6.*
9. *Yuttana Kumsuwan, Suttichai Premrudeepreechacharn, Hamid A. Toliyat, Modified direct torque control method for induction motor drives based on amplitude and angle control of stator flux, Electric Power Systems Research, Volume 78, Issue 10,2008,Pages 1712-1718,ISSN 0378-7796.*
10. *Hu, Jiefeng & Zhu, J.G. & Dorrell, David. (2014). Model-predictive direct power control of doubly-fed induction generators under unbalanced grid voltage conditions in wind energy applications. Renewable Power Generation, IET. 8. 687-695. 10.1049/iet-rpg.2013.0312.*
11. *Kou, Peng & Liang, Deliang & Li, Jing &GAO, Lin & Ze, Qiji. (2017). Finite-Control-Set Model Predictive Control for DFIG Wind Turbines. IEEE Transactions on Automation Science and Engineering. PP. 1-10. 10.1109/TASE.2017.2682559.*
12. *Wenjie Chen and Frede Blaabjerg, "Doubly Fed Induction Generator Wind Turbine Systems Subject to Recurring Symmetrical Grid Faults," 201510.1109/TPEL.2015.2418791, IEEE Transactions on Power Electronics.*

13. *Y. Zhang and J. Jiao, "Model Predictive Rotor Current Control for Doubly Fed Induction Generators under Unbalanced Grid Voltages," 2018 IEEE International Power Electronics and Application Conference and Exposition (PEAC), Shenzhen, 2018, pp. 1-5.*

14. *P. Flannery and G. Venkataramanan, "Unbalanced Voltage Sag Ride-Through of a Doubly Fed Induction Generator Wind Turbine with Series Grid Side Converter," 2008 IEEE Industry Applications Society Annual Meeting, Edmonton, AB, 2008, pp. 1-8.*