An improved control strategy of low voltage ride through enhancement capability for DFIG based wind turbine: A review

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Abstract- Across many countries wind turbines generation systems (WTGS) have been installed over the past few years. However, the power generated is inconsistent due to wind speed variations. The power generated and the losses in wind turbine changes corresponding with change in wind speed. The only type of machine which can generate power at speeds below the fixed speed is Doubly Fed Induction Generator (DFIG). But DFIG is oversensitive to grid faults, which makes to fail the Bidirectional converters and dc link capacitor due to high inrush current and over voltage. Hence protection techniques are required to prevent DFIG from grid fault. In order to stay connected to the grid during voltage dip, low voltage ride through (LVRT) is an essential phenomenon. The above said problem is rectified by using eight protection techniques to prevent DFIG during voltage dip are implemented. These eight methods are Blade pitch angle control, DC Chopper, crowbar circuit, series dynamic resistance, Battery energy storage system, switch-type fault current limiter, Dynamic Voltage Restorer and FACTS Devices. The various hardware requirements and different control schemes are studied and discussed in this paper to enhance LVRT capability. Torque, speed and thermal stress are analyzed for symmetrical and unsymmetrical fault conditions.

Index Terms- Doubly-fed Induction Generator (DFIG), Low Voltage Ride Through (LVRT), Blade pitch angle control, Crowbar circuit, DC Chopper, series dynamic resistance (SDR), Battery energy storage system (BESS), Switch-Type Fault Current Limiter (STFCL), DVR , FACTS Devices

I. INTRODUCTION

Wind energy is a non conventional and clean renewable source of energy. On account of depletion of fossil fuel and global warming many countries have installed wind turbine generation systems (WTGS) to maintain continuity of power supply. Electrical power generated from wind is of low cost, when compared with other renewable energy generating systems [1]. The variable speed wind turbine (VSWT) is superior to the fixed speed wind turbine because of its ability to draw power at low wind speed. Doubly-fed induction generator (DFIG) is one such example. It is cost effective, compatible, light weight and can also control active and reactive power of the system. [2]. The stator and the rotor of DFIG are directly connected to the grid using convertors. There are two converters, rotor side converter (RSC) and grid side converter (GSC) which is bidirectional in nature. A Dc link capacitor is connected between both the converters. DFIG is sensitive to power grid disturbances in case of voltage sags [3]. During this fault the terminal voltage across the grid is below the threshold value, in this case the stator current increases, which correspondingly increases the value of rotor current and flows through RSC [4]. At this instant RSC fails due to high inrush rotor current and dc link capacitor fails due over voltage. Sag withstanding capability of DFIG is dependent on Low Voltage Ride Through (LVRT) phenomenon [5]. The turbine's stability should be maintained during a fault, and it should remain linked to the grid even if the voltage loss is critical. When the voltage falls below the curve's value, the turbine is cut off from the power grid [6]. Some protection techniques required to protect the converters from the above fault are discussed in this review. The schematic diagram of DFIG based wind turbine is show in Figure 1.

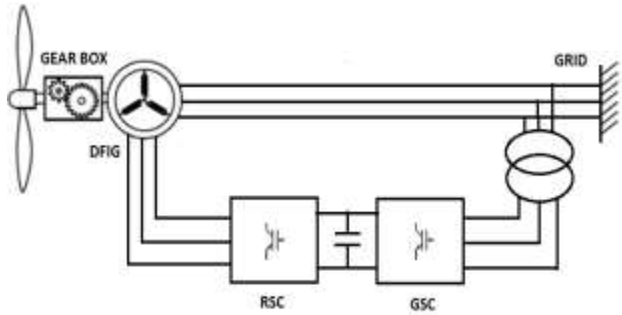

Figure 1. Configuration of DFIG based wind turbine

II. GRID-CODE AND REQUIREMENTS

Wind turbines are established in areas with sufficient wind power density and require necessary provision to connect to the grid. However, with the increase in force of wind power there was a requirement for establishing standard operation procedure. The wind turbine grid code suggests that these farms should help in control of power just as conventional systems do and should stay connected even when there is fault occurrence [83]. The important requirements are active power regulation and frequency control, voltage regulation capability and reactive power/power factor, terminal voltage and supply frequency discrepancy limits, as well as FRT capability [7-10].

The grid code main requirements are as follows

A. Active Power

The generator used in wind turbine must be able to control active power, this will help in injecting a stable frequency and avoid overloading of transmission lines large step up in voltages and in rush currents during start and stop operations. When power is increased in the system during faults in should not cause large power surges.

B. Reactive Power

Wind power generating systems needs reactive power support. To compensate the reactive power requirement and to maintain the reactive power balance and power factor that needs static capacitor bank or through dynamic VAR devices like STATCOM are available [84]. The reactive power leads to increase in loss, overheating and degrading of lines.

C. Frequency requirements

To obtain power balance in any system, the supply frequency plays the major role. Whenever there is an increase in demand it leads to a fall in the frequency value, whenever demand decreases frequency increases. Thus the frequency varies from 49.5-50.5 Hz due to the power imbalance. This occurrence can be rectified using primary and secondary control of Conventional Synchronous Generator.

D. Low Voltage Ride-Through

If the occurring voltage sag is below the threshold value the turbine remains connected. The generation of power from wind turbine is not affected if the fault is cleared due to voltage dip naturally. Disconnecting the WT from large wind farm produces higher value of power generation loss.

Invariant grid code requires large wind farms should withstand voltage sags for few percentages for specified period of time. These limitations are called FRT or LVRT capability requirement. A typical LVRT curve shows voltage versus time characteristic [11] as shown in Figure 2

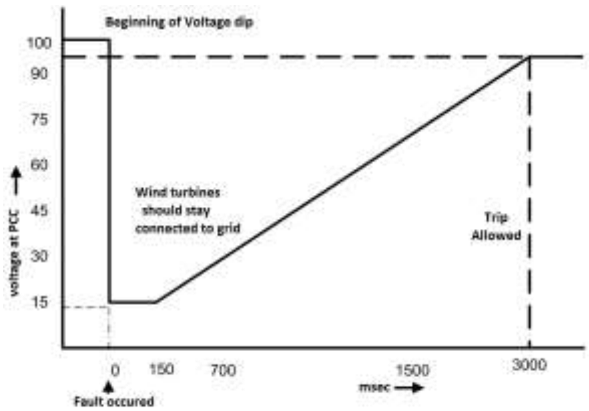

Figure 2. Typical LVRT curve

III. REVIEW OF WIND TURBINE LVRT TECHNIQUES BASED ON DOUBLY FED INDUCTION GENERATORS

LVRT capability improved in DFIGs, using several methods as discussed in this literature.

A. Blade pitch angle control

Pitch angle control refers tuning the angle of movements of the blades of rotor to control the production of power. The control system is adjusted in order to keep the blade pitch within the operating limits of change in wind speed. When compared with passive stall, pitch angle control captures more power from available wind speed. On the basis of the pitch control mechanism, wind turbine can be subdivided as fixed pitch Wind turbine, Variable pitch wind turbines. There are varieties of blades manufactured by different manufacturers. Variable pitch is required mainly for big machines in order to reduce aerodynamic loads and draw more power during fixed speed operation. There should be proper maintenance and for small machines fixed pitch is more suitable [12]

B. Crowbar methods

The crowbar protection circuit consists of three phase diode rectifier, the output of rectifier is connected to bypass resistor [13-15]. The passive crowbar circuit bypasses RSC using crowbar resistor, when DFIG is interrupted. But active crowbar circuit connects crowbar braking resistor when essential and disconnects it to operate DFIG control without any disturbance that occurs to DFIG. In this work, the active crowbar circuit consists of a diode rectifier, whose output is linked to a crowbar braking resistor in series with an IGBT with on/off control for DFIG interruption is shown in Figure.3

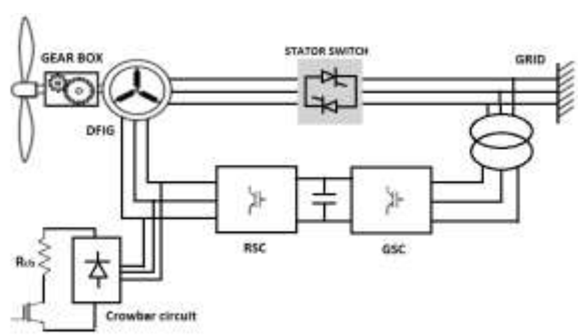

Figure 3. Crowbar Protection circuit

Whenever there is a drop in terminal voltage across the grid below the fixed value the braking resistor comes in contact with DFIG as the crowbar is switched on, the RSC is switched off. When the terminal voltage increases the braking resistor gets disconnected from the rotor of DFIG as crowbar is switched off. The crowbar circuit connects the rotor of generator and prevents the power converter and improves LVRT capacity [85]. The main advantage of Crowbar protection scheme is which prevents converter and generator during fault. The main disadvantage is that when there is fault occurrence as the crowbar circuit comes into play the DFIG loses its control and absorbs power from the grid which leads to the further dip in the voltage. The value of braking resistor should be carefully calculated to minimize the losses and to achieve adequate damping. Another crowbar mechanism is presented in series to the stator of the DFIG linked to the grid to avoid the foregoing problems [16]. This scheme involves bidirectional conduction switch (stator switch) which connects stator of DFIG to grid, but special attention should be taken to reduce the switching losses [17].

C. DC Chopper Protection circuit

The DC Chopper protection circuit has a chopping resistor cascaded to a dc link capacitor. An IGBT is connected in series with chopping resistor, depending on the rate of voltage across the dc link the chopper may be turned on or turned off. Since the dc chopper is connected across dc link which protects the converter and dc link capacitor from over voltage during low voltage grid fault [18]. The DC chopper circuit is shown in Figure 4.

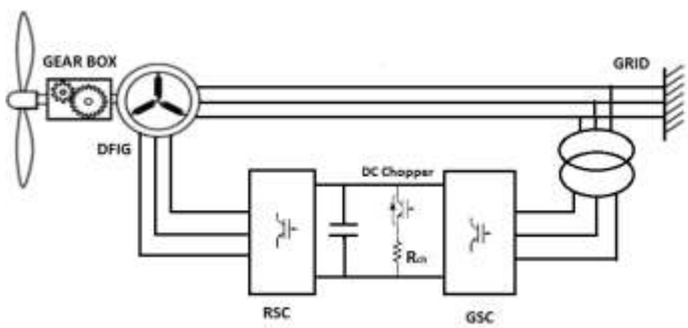

Figure 4. DC Chopper circuit

The dc chopper is activated whenever the voltage across the dc link rises, assisting in the maintenance of a stable voltage; the RSC is still connected to the DFIG rotor. When the voltage across the dc link is lower than preferred value the dc chopper is turned off, thus dc chopper circuit prevents converter and link capacitor during grid fault [19].

D. SDR Protection circuit

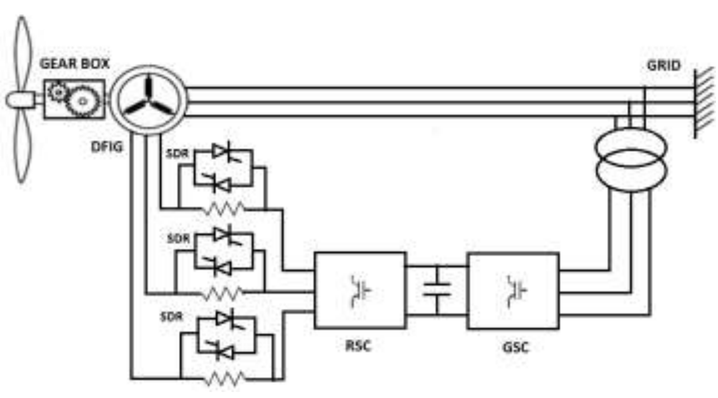

Figure 5. SDR Protection circuit

The series dynamic resistor is linked between the rotor of the DFIG and the RSC in this technique. The bidirectional switches connected across the SDR limits the value of over current entering to RSC during fault condition, thus RSC is protected from over current fault. The SDR Protection circuit is shown in Figure 5. When the terminal voltage across the grid is normal, the switches are in ON condition and series dynamic resistor are by passed, thus allows the currents entering to RSC. When the terminal voltage falls below its rated value, the switches are turned off, and SDR is linked between the rotor of DFIG and RSC, the current entering RSC is limited. During various grid faults SDR protects the converter from overvoltage and over current. Hence the charging current and voltage across the dc link capacitor are within the safe value. The distinction between crowbar and SDR is that crowbar and DC chopper are shunted and SDR is in series.

E. Battery Energy Storage System

The objective of battery storage energy system is to maintain a constant voltage across dc bus link. It comprises of DC-DC bidirectional Convertor in connection to dc link capacitor. The battery-side converter control is shown in Figure 6. During fault occurrence the over voltage across the link gets regulated and absorbed by storage system, therefore improving the LVRT capability [20].

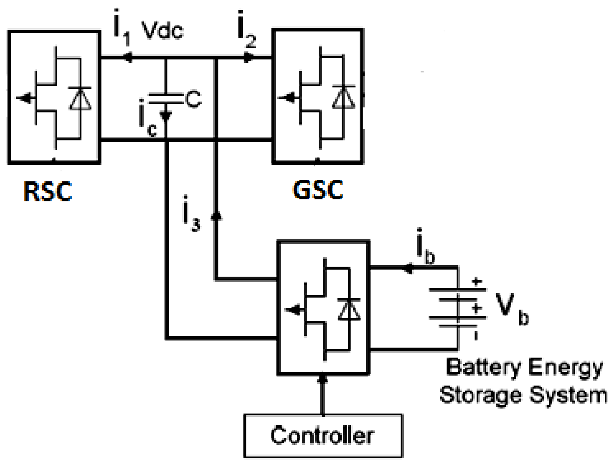

Figure 6. Battery energy storage systems

F. *Switch-Type Fault Current Limiter*

Switch type fault current limiter (STFCL) uses fault-current limiting inductors (Li) connected to stator of DFIG to enhance LVRT capability. The STFCL circuit consists of fault-current limiting inductors, isolation transformers, a diode bridge rectifier, a static switch (Sd), a snubber capacitor (Cf), and a fault energy absorption bypass resistor in series to capacitor (Ra and Ca). When static switch (Sd) is turned on Li is bypassed, similarly when Sd is turned off Li is added to the stator of DFIG. Snubber capacitor inhibit the transient overvoltage when Sd in off condition. Ra limits the fault current entering to Ca and fault energy absorption capacitor is used to store excessive energy supplied to stator. STFCL protects DFIG from over current, overvoltage, over torque and limits rotor back EMF voltage. Thus it improves the RSC controllability; it also provides sufficient reactive power to grid. The crowbar method of protection by passes the fault current through bypass resistor but in case of STFCL the fault current is reduced by using Ra and Ca. As a result, the STFCL technique of grid protection mitigates more serious grid concerns [21, 82]. The Switch-Type Fault Current Limiter Protection circuit is shown in Figure 7.

IV. Reactive Power Injection based

A. LVRT Techniques

Dynamic voltage restorer (DVR) and FACTS devices like STATCOM and UPFC are regularly used to introduce the reactive power during grid fault condition to legitimately ride through low voltages which are clarified as following.

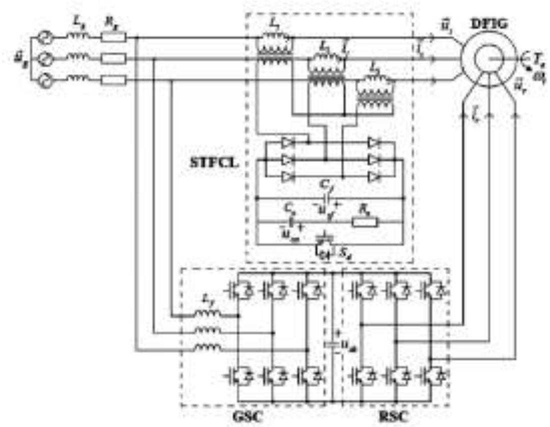

Figure 7. Switch-Type Fault Current Limiter

B. Dynamic Voltage Restorer

To compensate the voltage sag and voltage dips DVR is connected in series to the grid using coupling transformer [81]. The rating of converter depends upon the value of dips. This device acts as series compensator used to optimize the performance of LVRT. It is likewise expressed that dc capacitor size should not surpass as far as possible to guarantee better LVRT performance of DFIG based wind turbine[33]. The DVR circuit is shown in Figure 8. However, they are generally not used in systems that are subject to protracted reactive power deficiencies (ensuing low voltage conditions) and in systems that are vulnerable to voltage collapse. In most of the condition [25] DVR based arrangement is best suited for LVRT enhancement solution.

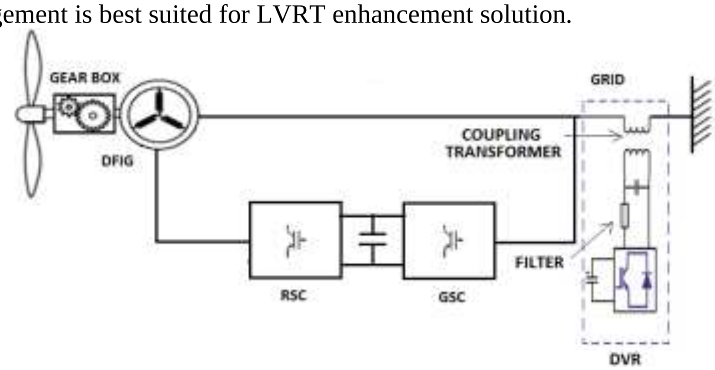

Figure 8. Switch-Type Fault Current Limiter

C. FACTS Devices

For better power exchange capability and stability series ad shunt based FACTS compensation methods are used in power system for improving power quality[26]. FACTS based devices like SVC and STATCOM works much better during LVRT enhancement. Under different grid fault conditions [27-28] LVRT based Optimization of DFIG WTs are discussed. For superior LVRT improvement [29] Unified power flow controller (UPFC) is inserted for reactive power injection.

D. Modified Vector Control Algorithms

Typical vector control of DFIG under steady state for GSC and RSC as avowed in [23] but its respective dynamic performance is worst. The modified vector control of DFIG is stated below. Virtual resistance system for rotor current based LVRT improvement is implemented in [24].For personalized vector control Feed-forward transient current control (FFTCC) of RSC is discussed in [30]. Emulating control using inductance is discussed in [32]. Finally for achieving better LVRT solution Virtual damping flux based method is discussed in [31]

Table 1. Hardware requirement to improve LVRT DFIG performance

Solution	Source
Static switches for power conversion	[34]
Rotor side series converter	[35]
Super capacitor as energy storage system to emphasize the DC link	[36]
Six-switch conventional grid side converters is replaced by nine-switch converter	[37]
Arrangement of series and parallel GSC	[38]
Implementation of SMES	[39]
Super capacitor energy storage system (SC)	[40]
STATCOM connected with Super capacitor energy storage system	[41]
Stator connected with anti-parallel thyristor and IGBT for higher current carrying capability	[42]
A protective arrangement consisting of an uncontrolled rectifier, two sets of IGBT an inductor, diode and switch	[43,44]
Superconducting fault current limiter (SFCL)	[45,46]

V. PERFORMANCE OF DFIG WITHOUT ANY LVRT PROTECTION

The primary objective of this paper is to protect DFIG based wind generator from short circuit fault during LVRT. In case of symmetrical faults during starting and end of fault, rotor circuit current increases to higher value. But in case of unsymmetrical faults the winding stress of DFIG is more compared with symmetrical faults.

At the beginning of unsymmetrical fault the rotor current starts increasing gradually, finally it becomes constant until the fault ends. The thermal stress on the winding of DFIG and converter is more in unsymmetrical faults when compared with symmetrical faults, also torque and speed fluctuations is more in case of unsymmetrical faults hence the impact of mechanical stress is more in case of DFIG based wind turbine, without any LVRT protection [22].

Table 2. Various control approaches to improve DFIG's LVRT

Solution	Source
Control scheme activates switch during the fault condition	[47]
Magnetizing current controller	[48]
Effective resistance higher current limiter	[49]
Genetic algorithm based fuzzy controller	[50]
Real and reactive power stream control using various reference under fault and normal condition	[51]
Effective resistance utilizing the RSC voltage	[52]
A vector-controller support non-optimal controller	[53]
Implementation of a controller for an unbalanced dip in voltage with regards to RSC and GSC	[54]
For imbalanced voltage circumstances, a controller consisting of a bidirectional resonant-frequency compensator and a PI control device is used	[55]
Momentary current controller based on feed-forward	[56]
Controller for feedback linearization	[57]
Storage of electrical power from kinetic energy wind turbine	[58]
Internal hysteresis current control and exterior power-based control loop	[59]
An adjustable oscillating controller	[60]
Conversion of kinetic energy from waste energy	[61]
Using two models to regulate the degree of flexibility	[62]
Decentralized linear feedback controller	[63]
Application of analogous soft torque synchronized control constant active power	[64]
Control approach to track flux link	[65]
Control approach to track phase angle	[66]
A nebulous controller	[67]
Non-optimal vector controller	[68]
An indiscriminate controller for DC voltage controller	[69]
Controller for unbalanced voltage drop	[70]
Controller for second order discontinuous control signal	[71]
Direct form indication adaptive in-house controller	[72]
Implementation of a control system that specifies numerous reference values for real and reactive powers in both stable and unsteady settings	[73]
After an external short circuit, grid-powered WECS are re-established under stable conditions	[74]
For programming unreliable LVRT states, vibrant power control for dynamic control is employed	[75]
A controller to monitor DC link voltage	[76]
A control method to consider dynamic magnetizing current in stator circuit	[77]
A controller for nonlinear application	[78]
Three individual current controllers utilized for symmetrical elements and quadratic linear regulator	[79]
Implementation of stator magnetizing flux linkage in rotor current controller inference and DC composition	[80]

VI. CONCLUSION AND FUTURE WORK

Low voltage ride through (LVRT) is an essential method required for the wind turbine to satisfy the grid code requirement. Different methods of LVRT protection schemes are discussed. The above methods are studied and analyzed in this paper. Since DFIG is oversensitive to grid voltage variations, few control techniques are implemented to prevent the bidirectional converter disconnecting from the grid. Crowbar method of protection bypasses the fault current, but in case of STFCL the value of fault current and rotor back EMF are limited. STFCL has excellent LVRT enhancing capability, when compared with crowbar method of protection. Advanced control strategies have also being discussed to improve LVRT performance. Future research work should be carried on DFIG optimal performance to meet grid code constraint under various grid faults.

REFERENCES

[1] S. M. Muyeen, "Wind Energy Conversion Systems," Green Energy and Technology, Springer-Verlag London Limited 2012.

[2] R. Cardenas, R. Pena, S. Alepuz, and G. Asher, "Overview of control system for the operation of DFIGs in wind energy application," IEEE Trans. Ind. Electron., vol. 60, no. 7, pp. 2776–2798, Jul. 2013

[3] H.T. Jadhav and R. Roy, "A comprehensive review on the grid integration of doubly fed induction generator," International Journal of Electrical Power & Energy Systems, vol. 49, pp. 8-18, July 2013.

[4] I. Erlich, H. Wrede, and C. Feltes, "Dynamic Behavior of DFIG-Based Wind Turbines during Grid Faults," in the Proc. of the 2007 IEEE Power Conversion Conference (PCC '07), pp. 1195-2000, April 2-5, 2007, Nagoya, Japan.

[5] Ayaz Ahmad and Rajaji Loganathan, "Development of LVRT and HVRT Control Strategy for DFIG Based Wind Turbine System," in the Proc. of the 2010, IEEE International energy conference, pp. 316-321,18-22 Dec.2010, Manama

[6] Sharad W. Mohod and Mohan V. Aware, "Power quality and grid code issues in wind Energy conversion Systems," Energy engineering, An update on Power Quality, Chapter 2, INTECH, march-2013

[7] M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," IET Renewable Power Generation, vol. 3, no3, pp. 308-332, September 2009.

[8] B. Singh and S.N. Singh, "Wind power interconnection into the power system: A review of grid code requirements," The Electricity Journal, vol. 22, no5, pp. 54-63, 2009.

[9] B. Singh, S.N. Singh and L. Wang, Electric grid connection and system operational aspect of wind power generation, in Wind Energy Conversion System: Technology and Trends, S.M. Muyeen, (Eds.), Springer-Verlag: UK 2012.

[10] M. Mohseni and S.M. Islam, "Review of international grid codes for wind power integration: Diversity, technology and a case for global standard," Renewable and Sustainable Energy Reviews, vol.16, no6, pp. 3876-3890, August 2012.

[11] F. Iov, A. D. Hansen, P. Sørensen and N. A. Cutululis, "Mapping of grid faults and grid codes," Tech. Rep. Risø-R-1617(EN), Riso Nat. Lab., Tech. Univ. Denmark, Roskilde, Denmark, Jul. 2007.

[12] Muhammad H. Rashid, Ph.D, Fellow IET (UK), Fellow IEEE (USA), "Power Electronics Handbook devices, circuits and applications" Third edition, 2011, Elsevier Inc

[13] J. G. Slootweg, H. Polinder, and W. L. Kling, "Dynamic modeling of a wind turbine with doubly fed induction generator," in Proc. IEEE Power Eng. Soc. Summer Meeting, Vancouver, BC, Canada, July 15- 19, 2001.

[14] S. Seman, J. Niiranen, and A. Arkkio, "Ride-through analysis of doubly fed induction wind power generator under unsymmetrical network disturbance," Power Systems, IEEE Transactions on, vol. 21, no. 4, pp. 1782–1789, Nov. 2006.

[15] C. Wessels and F. W. Fuchs, "Fault ride through of DFIG wind turbines during symmetrical voltage dip with crowbar or stator current feedback solution" IEEE Energy conversion Sept 2010.

[16] K.E. Okedu, S.M. Muyeen, R. Takahashi and J. Tamura, "Wind farms fault ride through using DFIG with new protection scheme," IEEE Trans. Sustainable Energy, vol. 3, n°3, pp. 242-254, April 2012.

[17] Marwa Ezzat, Mohamed Benbouzid, S.M. Muyeen and Lennart Harnefors, "Low-Voltage Ride-Through Techniques for DFIG-Based Wind Turbines: State-of-the-Art Review and Future Trends," IEEE IECON 2013, Nov 2013, Vienne, Austria.pp.7681-7686,2013.

[18] I. Erlich, J. Kretschmann, J. Fortmann, S. Mueller-Engelhardt, and H. Wrede, "Modeling of wind turbines based on doubly-fed induction generators for power system stability studies," IEEE Trans. Power Syst., vol. 22, no. 3, pp. 909 919, Aug. 2007.

[19] I. Erlich, H. Wrede, and C. Feltes, "Dynamic behavior of DFIG-based wind turbines during grid faults," in Proc. Power Converters. Conf, Nagoya, Japan, Apr. 2-5, 2007.

[20] Dongdong Li, IEEE M ember,and Huajie Zhang, "A combined protection and control strategy to enhance the LVRT capability of a wind turbine driven by DFIG," 2nd IEEE international symposium on power electronics for distributed generation systems, pp. 703-707,China, June 2010.

[21] Wenyong Guo, Member, IEEE, Liye Xiao, Shaotao Dai, Yuanhe Li, Xi Xu, Weiwei Zhou, and Luo Li, "LVRT Capability Enhancement of DFIG With Switch-Type Fault Current Limiter," IEEE transactions on industrial electronics, vol. 62, no. 1, Jan 2015.

[22] Nagy Y. Abed, Senior Member, IEEE, M. M. Kabsha, and Gabr M. Abdlsalam, Member, IEEE, "Low Voltage Ride-Through Protection Techniques for DFIG Wind Generator,"IEEE Power and energy society general meeting (PES), 2013.

[23] S. Müller, M. Deicke, and D. W., & Rik Doncker, "Doubly fed induction generator systems for wind turbines," Ind. Appl. Mag. IEEE, vol. 8, no. 3, pp. 26–33, 2002.

[24] J. López, E. Gubía, E. Olea, J. Ruiz, and L. Marroyo, "Ridethrough of wind turbines with doubly-fed induction generator during a voltage dip," IEEE Trans. Ind. Electron., vol. 56, no. 10, pp. 4246–4254, 2009.

[25] O. Abdel-Baqi and A. Nasiri, "Series voltage compensation for DFIG wind turbine low-voltage ride through solution," IEEE Trans. Energy Convers., vol. 26,no. 1, pp. 272–280, 2011.

[26] T. J. Hammons and S. K. Lim, "Flexible ac transmission systems (facts)," Electr. Mach. Power Syst., vol. 25, no.1, pp. 73–85, 1997.

[27] K. E. Okedu, S. M. Muyeen, R. Takahashi, and J. Tamura, "Comparative Study of Wind Farm Stabilization Using Variable Speed Generator and Facts Device," pp.569–572, 2011.

*[28] B. Mukhopadhyay and R. K. Mandal, "Voltage compensation using PSO-PI controlled STATCOM in a DFIG-based grid-connected wind energy system," Int. Conf. Electr. Power Energy Syst. ICEPES 2016, pp. 88–
93, 2017.*

[29] G. E. Ahmed, Y. S. Mohmed, and O. M. Kamel, "Optimal STATCOM controller for enhancing wind farm power system performance under fault conditions," 2016 18th Int. Middle-East Power Syst. Conf. MEPCON 2016 -Proc., no. 1, pp. 226–233, 2017.

[30] Y. M. Alharbi, A. M. S. Yunus, and A. Abu Siada, "Application of UPFC to improve the LVRT capability of wind turbine generator," Univ. Power Eng. Conf. (AUPEC), 2012 22nd Australas., pp. 1–4, 2012.

[31] J. Liang, W. Qiao, and R. G. Harley, "Feed-forward transient current control for low-voltage ride-through enhancement of DFIG wind turbines," IEEE Trans. Energy Convers., vol. 25, no. 3, pp. 836–843, 2010.

[32] R. Zhu, Z. Chen, X. Wu, and F. Deng, "Virtual Damping Flux-Based LVRT Control for DFIG-Based Wind Turbine," IEEE Trans. Energy Convers., vol. 30, no. 2, pp. 714–725, 2015

[33] Zakiud, Din, Jianzhong, Zhang, Zheng, Xu,"A review on Low Voltage Ride-though for DFIG based Wind Turbines,"PCIM Asia 2018; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy management ,pp. 268-274, 2018.

[34] Kasem AH, El-Saadany EF, El-Tamaly HH, and Wahab MA.An improved fault ride- through strategy for doubly fed induction generator-based wind turbines. Renew Power Gener IET 2008; 2:201-14.

[35] Abdel-Baqi O, Nasiri A. A dynamic LVRT solution for doubly fed induction generators. Power Electron IEEE Trans2010; 25:193–6.

[36] Abbey C, JoosG. Super capacitor energy storage for wind energy applications. Ind ApplIEEETrans2007; 43:769–76.

[37] KanjiyaP, AmbatiBB, KhadkikarV.An ovel fault-tolerant DFIG-based wind energy conversion system for seamless operation during grid faults. Power Syst IEEETrans2014; 29:1296–305.

[38] Flannery PS, Venkataramanan G.A fault tolerant doubly fed induction generator wind turbine using a parallel grid side rectifier and series grid side converter. Power Electron IEEE Trans 2008; 23:1126–35.

[39] Jing S, YuejinT, YajunX, LiR, JingdongL. SMES based excitation system for doubly-fed induction generator in wind power application. Appl Supercond IEEE Trans2011; 21:1105–8.

[40] GkavanoudisSI, DemouliasCS.A combined fault ride-through hand power smoothing control method for full-converter wind turbines employing super-Capacitor energy storage system. Electric Power SystRes2014; 106:62–72.

[41] Rahim AHMANowickiEP. Super capacitor energy storage system for fault ride-through of a DFIG wind generation system. Energy Convers Manag 2012; 59:96–102.

[42] Petersson A, LundbergS, ThiringerT.ADFIG wind turbine ride-through system. Influence on the energy production. WindEnergy2005; 8:251–63.

[43] Vinothkumar K, SelvanMP.Novel scheme for enhancement of fault ride- through capability of doubly fed induction generator based wind farms. Energy ConversManag2011; 52:2651–8.

[44] Vinothkumar K, SelvanMP.Novel coordinated converter control (3C) strategy for enhancement of fault ride-through capability of doubly fed induction generator wind farms. Electric Power Compon Syst 2011; 39:1493–506.

[45] WenyongG,LiyeX,ShaotaoD.Enhancinglow-voltage ride-through cap- ability and smoothing output power of DFIG with a super conducting fault- current limiter-magnetic energy storage system. Energy ConvIEEETrans 2012;27:277–95.

[46] Elshiekh ME, MansourDA, AzmyAM. Improving fault ride-through cap- ability of DFIG-based wind turbine using super conducting fault current limiter. ApplSupercond IEEE Trans2013; 235601204-.

[47] Lima FKA,LunaA, RodriguezP, WatanabeEH, Blaabjerg F.Rotor voltage dynamics in the doubly fed induction generator during grid faults. Power Electron IEEE Trans 2010;25:118–30.

[48] Mendes VF, deSousa CV, Silva SR, Cezar Rabelo B, Hofmann W. Modeling and ride-through control of doubly fed induction generators during symmetrical voltage sags. Energy Convers IEEE Trans2011;26:1161–71. [49] Sheng H, XinchunL, YongK, XudongZ.An improved low-voltage ride- through control strategy of doubly fed induction generator during grid faults. PowerElectronIEEETrans2011; 26:3653–65.

[50] Vrionis TD,KoutivaXI,VovosNA.Agenetic algorithm-based low voltage ride-through control strategy for grid connected doubly fed induction wind generators. Power systIEEE Trans2014; 29:1325-34.

[51] DA costa JP, Pinheiro, Degner T, Arnold G Robust, Controller for DFIGs of grid-connected wind turbines. Ind Electron IEEE Trans2011;58:4023-38.

[52] Hu S, LinX, KangY, ZouX.An improved low-voltage ride-through control strategy of doubly fed induction generator during grid faults. Power Electron IEEE Trans2011; 26:3653–65.

[53] Mohseni M, IslamS,MasoumMA. Fault ride-through capability enhancement of doubly-fed induction wind generators. Renew Power GenerIET 2011; 5:368–76.

[54] Gomis-Bellmunt O, Junyent-Ferre A, Sumper A, Bergas-Jan J. Ride-through control of a doubly fed induction generator under unbalanced voltage sags. Energy ConversIEEETrans2008; 23:1036–45.

[55]Hailing X,JiabingH, Yikang H.Integrated modeling and enhanced control of DFIG under unbalanced and distorted grid voltage conditions. EnergyCon - veers IEEETrans2012;27:725–36.

[56] Jiaqi L, Wei Q, Harley RG, Feed-forward transient current control for low - voltage ride-through enhancement of DFIG wind turbines. Energy Converse IEEE Trans2010;25:836–43.

[57] Leon AE,MauricioJM,SolsonaJA. Fault ride -through enhancement of DFIG - based wind generation considering unbalanced and distorted conditions. Energy convers IEEE Trans 2012;27:775-83.

[58] Xie D,XuZ,YangL, OstergaardJ,XueY, WongKP. A comprehensive LVRT control strategy for DFIG wind turbines with enhanced reactive power support. Power Syst IEEE Trans 2013;28:3302–10.

[59] Mohseni M,IslamSM.Transient control of DFIG-based wind power plants in compliance with the Australian grid code. Power Electron IEEE Trans 2012;27:2813–24.

[60] Mishra Y,MishraS, TripathyM,SenroyN, DongZY. Improving stability of a DFIG-based wind power system with tuned damping controller. Energy ConversIEEETrans2009;24:650–60.

[61] YangL ,XuZ, OstergaardJ, DongZY, WongKP. Advanced control strategy of DFIG wind turbines for power system fault ride through. Power Syst IEEE Trans2010;27:713–22.

[62] Campos-Gaona D, Moreno-GoytiaEL, Anaya-LaraO.Fault ride-through improvement of DFIG-WT by integrating a two-degrees-of-free dominter-nalmodelcontrol.IndElectronIEEETrans2013;60:1133–45.

[63] Hossain MJ,SahaTK,MithulananthanN, PotaHR.Control strategies for augmenting LVRTcapability of DFIG sin interconnected power systems.Ind Electron IEEETrans2013;60:2510–22.

[64] Hu J,XuH,HeY.Coordinated control of DFIG's RSCandGS Cundergen - eralized unbalanced and distorted grid voltage conditions. Ind Electron IEEE Trans2013;60:2808–19.

[65] Shuai X,GengY,HonglinZ, HuaG. An LVRT control strategy based on flux linkage tracking for DFIG-based WECS. Ind Electron IEEE Trans 2013;60:2820–32.

[66] Bu SQ,WenjuanD,WangHF,GaoS.Power angle control of grid-connected doubly fed induction generator wind turbines for fault ride-through. Renew PowerGenerIET2013;7:18–27.

[67] Flannery PS,Venkataramanan G.Unbalanced voltages a gride - through of a doubly fed induction generator wind turbine with series grid - side converter. Ind ApplIEEETrans2009;45:1879–87.

[68] Mohseni M,MasoumMAS,IslamSM. Low and high voltage ride-through of DFIG wind turbines using hybrid current controlled converters. Electric Power Syst Res 2011;81:1456–65.

[69] Rahimi M,ParnianiM.Grid-fault ride-through analysis and control of wind turbines with doubly fed induction generators. Electric Power Syst Res 2010;80:184–95.

[70] Hachicha F, KrichenL. Rotor power control in doubly fed induction generator wind turbine under grid faults. Energy2012;44:853–61.

[71] Benbouzid M, Beltran B, Amirat Y, Yao G, Han J, Mang H. Second-order sliding mode control for DFIG – based wind turbines fault ride – through capability enhancement.ISATrans2014;53:827–33.

[72]Amuthan N, Melba P, Subburaj P, Sharmeela C, Ride-through and direct model reference adaptive internal model controller with rule-based adjust - ment mechanism for DFIG wind farms. IntJSustainEnergy2012;31:229–50.

[73] Hansen AD, Michalke G, Sourensen P, Lund T, lov F. Co-ordinated Voltage of DFIG Wind turbines in uninterrupted operation during grid faults. Wind Energy2007;10:51–68.

[74] Sun T,Chen Z, Blaabjerg F.Transient stability of DFIG wind turbines at an external short -circuit fault. Wind Energy 2005;8:345–60.

[75] Santos-Martin, Rodrigues-Amenedo JL, Arnaltes. Providing grid ride-through capability to a doubly fed induction generator under unbalanced voltage dips. Power Electron IEEE Trans2009;24:1747–57.

[76] YaoJ, LiH, LiaoY,ChenZ. An improved control strategy of limiting the DC- link voltage fluctuation for a doubly fed induction wind generator. Power Electron IEEE Trans 2008;23:1205–13.

[77] Hu J-b,HeY-k. Dynamic modeling and robust current control of wind - turbine driven DFIG during external AC voltage dip. JZhejiang University Sci A 2006;7:1757–64.

[78] Rahimi M, Parniani M.Transient performance improvement of wind turbines with doubly fed induction generators using nonlinear control strategy. Energy ConversIEEETrans2010;25:514–25.

[79] Alepuz S,Busquets-MongeS,BordonauJ, Martinez-VelascoJA,SilvaCA,Pontt J, etal.Control strategies based on symmetrical components for grid- connected converters under voltage dips. Ind Electron IEEE Trans 2009;56:2162–73.

[80] DaweiX, RanL, TavnerPJ, YangS.Controlof a doubly fed induction generator in a wind turbine during grid fault ride-through. Energy Converts IEEE Trans 2006; 21:652–62.

[81] Sajjad Tohidi, Behnam Mohammadi-ivatloo, Faculty of Electrical and Computer Engineering, University of Tabriz, Iran, Volume 57, May 2016, Pages 412-419.

[82] Srinivasan P, Dhandapani Samiappan, Improvement of LVRT capability by combining -switch type fault current limiter and super capacitor for DFIG based wind turbines, IIOABJ, vol. 8, (suppl 3):53-59.

[83] Srinivasan P, Dhandapani Samiappan, Modelling and simulation of HVRT and LVRT enhancement capability for doubly fed induction generator based wind energy conversion systems, International journal of Engineering and Technology, UAE, 7 (2.33) (2018) 405-408.

[84] Srinivasan P, Dhandapani Samiappan, LVRT Enhancement Capability of DFIG based WECS by Implementing STFCL-SMES, International Journal of Pure and Applied Mathematics, Volume 119 No. 16, 2018, 3495-3500.

[85] J. Li, Q. Qiu and M. Zhan, "An Improved Crowbar Control Circuit of DFIG during LVRT," 2021 IEEE 4th International Electrical and Energy Conference (CIEEC), 2021, pp. 1-6, doi: 10.1109/CIEEC50170.2021.9510598.