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Comprehensive Overview of Low Voltage Ride Through Methods of Grid Integrated Wind Generator

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ABSTRACT The wind power generation is a rapidly growing grid integrated renewable energy (RE) technology with an installed capacity of 539.291 GW. The capability of the wind energy conversion system (WECS) to remain integrated into the utility network in the case of low voltage events is called low-voltage ride-through (LVRT) capability. This paper offers a comprehensive overview of improvement techniques of the LVRT capability in WECS to increase the wind energy penetration level in the utility grid. Exhibited portrait manifests a broad spectrum of 1) wind turbines, 2) electrical generators used for wind power applications, 3) international grid codes applicable for grid integration of WECS, 4) LVRT fundamentals in WECS, 5) wind turbines LVRT methods by doubly fed induction generator (DFIG), 6) wind turbines LVRT methods by permanent magnet synchronous generators (PMSG), and 7) LVRT methods of wind turbines using squirrel cage induction generator (SCIG). This ready-reckoner paper critically reviews and classifies more than 190 research papers on LVRT issues, practices, and available technologies for grid integration in wind energy systems, and it aims to be a quick reference for the researchers, designers, manufacturers, and engineers working in the same field.

INDEX TERMS DFIG, grid codes, LVRT, PMSG, SCIG, wind energy conversion system.

I. INTRODUCTION

Penetration of renewable energy (RE) into the utility grid contributes significantly to reduce the greenhouse gases emission [1]. Wind energy has emerged as the most contributing RE source due to advantages such as free availability of wind, economical operation, utilization of the land around the wind generators (onshore, offshore), ability to exploit high power, zero pollution emission and relatively inexpensive construction [2]. Nowadays, wind energy power plants based on doubly fed induction generator (DFIG), permanent magnet synchronous generators (PMSG), and squirrel cage induction generator (SCIG) have extensively integrated into the utility grid [3]. A shut down of large scale wind power plants may have severe effects on transient and steady state stability of power system operation [4]. Therefore, consideration of low voltage ride through (LVRT) is an essence for wind generators for the case of grid faulty events. Wind generators must withstand voltage disturbances without getting disconnected from the grid. Simultaneously, at the point of common coupling (PCC), the voltage must reach 80% of the nominal value within 0.5 seconds and 95% within 15 seconds after the fault clearance [5]. For a grid with integrated large size wind power plants, LVRT technique is an effective way to achieve the aforementioned objectives. Hence, the multifold extensive research work is on the pathway to design the efficient wind energy conversion systems (WECSs), international grid codes and associated implementation of LVRT methods for wind turbines with WECSs, DFIG, PMSG, and SCIG based technologies. Thus, a comprehensive review and classification of existing methods in this regard are essential to accelerate the pace of associated research. This bibliographic guide book can help the researchers, designers, manufacturers, and engineers to increase the penetration level of wind energy in the utility grid network.

This manuscript aims to present a comprehensive overview of LVRT capability improvement of wind power plants. More than 190 research publications [1]–[199] are reviewed

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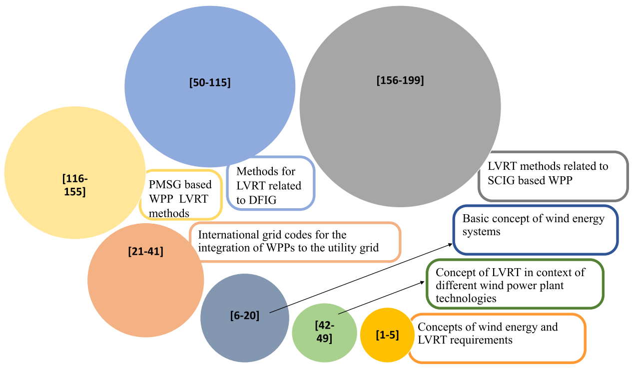

FIGURE 1. Classification of the 199 research papers.

critically and classified into the seven categories, shown in Fig. 1. First category [1]–[5] details general concepts of wind energy and LVRT requirement of wind power plants. Second category [6]–[20] comprises the basic concepts of the wind power plants (WPP), the design of wind turbines and wind generators. Third category [21]–[41] includes international grid codes used for the integration of WPPs to the utility grid. Fourth category [42]–[49] comprises the basic concepts of LVRT related to different types of wind generators. Fifth category [50]–[115] discusses different LVRT methods related to DFIG based wind power plants. Sixth category [116]–[155] includes articles on different LVRT methods related to PMSG based wind power plants. Seventh and final category [156]–[199] is on the different LVRT methods related to SCIG based wind power plants. However, some of the articles are broadcasted in more than one category depending on applications of proposed methods and their dominant field.

This paper is organized into nine sections, where the introduction and objectives are presented in Section I. Section II describes the basic concepts of wind energy conversion system (WECS). It includes wind turbine and wind power plants electrical generators. A brief description of international grid codes used for the integration of wind generators to the utility network has given in Section III. LVRT requirements of WECSs are detailed in section IV. Section V relates to LVRT methods of wind energy conversion systems by DFIG. LVRT methods for wind turbines using PMSG are described in section VI. Section VII deals with LVRT methods of SCIG based wind turbines. Future scope of research in the field of LVRT capability of wind power plants and hybrid power system is included in Section VIII. Finally, concluding remarks are included in section IX.

II. WIND ENERGY CONVERSION SYSTEMS

Wind energy conversion system (WECS) converts the kinetic energy (KE) of the wind into electrical energy. Fig. 2 depicts a diagram of WECS, where the wind turbine converts the KE of wind into mechanical energy (ME), and the electrical generator converts this ME into the electrical energy (EE). This EE is then injected into the utility network using the power electronics converters (PEC) and transformers [6]. For LVRT applications, WECSs are classified into three types: (1) fixed speed wind turbine (FSWT) which uses squirrel cage induction generator (SCIG), (2) variable speed wind turbine (VSWT) based on DFIG and (3) VSWT based on permanent magnet synchronous generator (PMSG) [7]. Reference [8] presents a detailed study of control principles and dynamic fault behavior of variable speed wind turbine based on PMSG. A design of DFIG-based wind energy conversion system with a useful LVRT capability is illustrated in Reference [9]. Reference [10] offers a detailed study of fixed speed wind generation system based on SCIG using the mechanical controller to improve the LVRT capabilities.

A typical practical WECS consists of aerodynamic system, mechanical and electrical parts, integration of which leads to the losses at various stages. Fig. 3 depicts the significant aerodynamics, electric generator, and converter losses respectively 58%, 10%, and 5% at various power conversion stages in a WECS. As a result, available wind power generates only 25-30% serviceable electrical power [11]. The aerodynamic system consists of rotor blades and drive train system. These are discussed briefly in following subsections.

A. WIND TURBINE

Wind turbine (WT) is an essential part of WECS. It consists of blades connected to the rotor shaft with the help of gearbox and rotor hub. This medium is used to convert the wind power into mechanical power (P_m) with the following relation to express power available on the generator shaft [12].

$$P_m = \frac{1}{2}\rho A v^3 C_p(\lambda, \beta) \tag{1}$$

In the above equation, Meaning of each variable and coefficients are as follows:

- C_p: the turbine performance coefficient;
- ρ: the density of air (kg/m^3);
- A: the area swept by rotor blades (m^2);
- v: the speed of wind (m/s);
- λ: tip speed ratio;
- β: blade pitch angle expressed in degrees;
- $C_p(\lambda, \beta)$: turbine power conversion coefficient C_p is a function of λ and β as defined by the following relation [13]:

$$C_p(\lambda, \beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) exp^{\left(\frac{-21}{\lambda_i}\right)} + 0.0068\lambda, \tag{2}$$

where λ_i is given by

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}. \tag{3}$$

Tip speed ratio λ is formulated in terms of the rotational speed of shaft (ω_m), wind speed (v) and radius of blades (R) as follows.

$$\lambda = \frac{R\omega_m}{v} \tag{4}$$

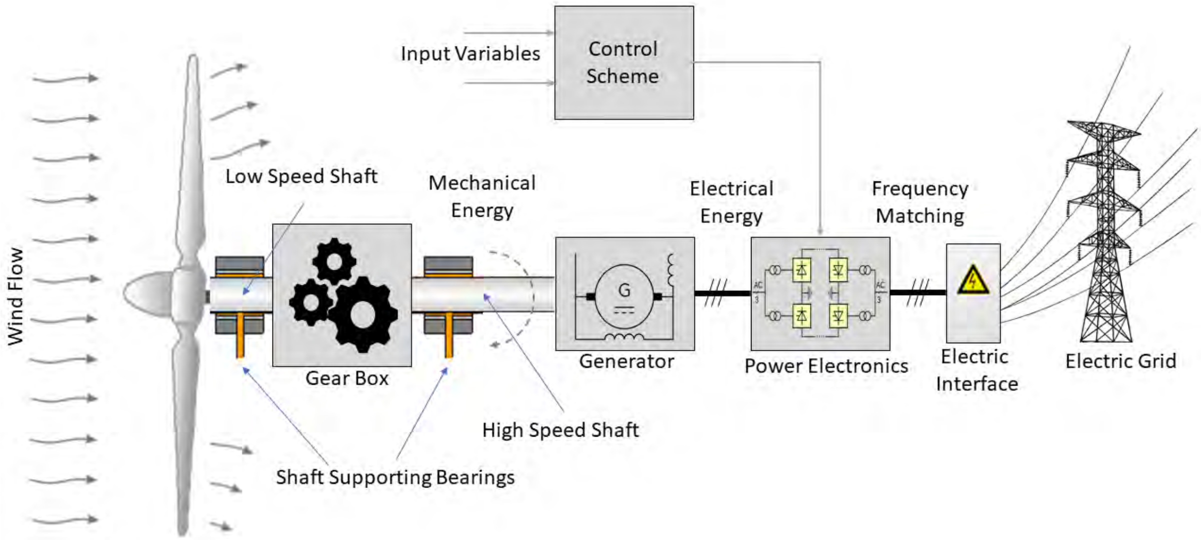

FIGURE 2. Wind energy conversion system.

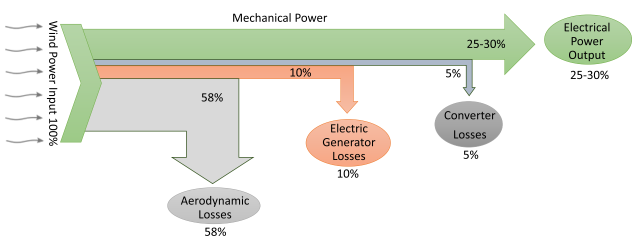

FIGURE 3. Power conversion stages of wind energy conversion system.

The following relation expresses the mechanical relation of the wind turbine using a single mass model of the drive train system [13]:

$$T_m = J_{eq}\frac{d\omega_m}{dt} + B\omega_m + T_e \tag{5}$$

In the above equation, the description of variables and coefficients are as follows:

T_m: the wind turbine driving torque;
J_{eq}: equivalent inertia of the generator and the turbine;
B: damping coefficient which represents rotational losses of both the turbine and the generator;
T_e: electromagnetic torque of the generator.

During grid faults, electrical power is reduced, and drive train of the turbine acts like an untwisted torsional spring. Due to this characteristic, generator speed oscillates with a frequency defined by the equation (6) [14].

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{J_{eq}}} \tag{6}$$

In the above equation, k is the equivalent stiffness constant of the shaft.

B. ELECTRICAL GENERATOR

Mechanical power P_m available with the rotor, equation (1), is converted into the electrical power using an electrical generator. Commonly used generators for wind power applications include DFIG, PMSG, and squirrel cage induction generator (SCIG) [15]. Section IV details the description of these generators. The report [16] provides mathematical modeling of the DFIG, its power converter model and filter model. The PMSG-based wind turbine system mathematical model and its control for LVRT improvement with a comparative study of synchronous and stationary proportional integral (PI) based flux weakening control method is reported in [17]. Detailed mathematical modeling of SCIG and its converters for improvement of LVRT capability using combinational voltage booster technique is presented in [18]. A simplified flux model of DFIG for the transient study is proposed in [19]. Reference [20] presents design and hardware in loop experiment of multi-loop adaptive control for the DFIG based wind turbine. Comprehensive modeling of the hybrid wind farm with SCIG and DFIG for capacity configuration and coordinated operation grid fault is reported in [15].

III. INTERNATIONAL GRID CODES FOR INTEGRATION OF WIND PLANTS TO UTILITY GRID

Integration of wind power plants with a large capacity to utility network has created many challenges to the transmission system operators (TSOs) such as electrical power quality and reliability and the stability of the electrical system. Such integration has encouraged the power system operators for revision of grid codes to include technical requirements of the wind power plants [21]. Revised grid codes impel the wind power plants to maintain better continuity and quality of power supply even during abnormal operating conditions of the network. Most common requirements of grid codes focus on LVRT capability, extended limits of voltage and frequency variations, regulation of active power, frequency

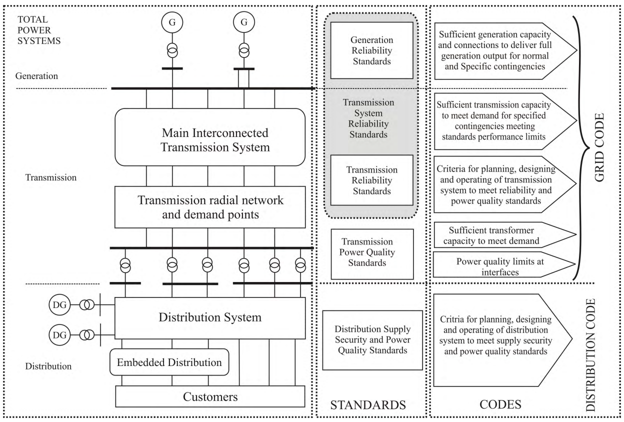

FIGURE 4. Grid codes and standards of malaysian power system network.

control, control of reactive power, power factor control and capability of voltage regulation [6]. For example, Fig. 4 depicts the Malaysian grid code requirement. The authors have provided a detailed study of current procedures and practices of grid code compliance of renewable power generation in [22]. Reference [23] presents a detailed study of grid code compliant controllers for multi-terminal high voltage DC (HVDC) to integrate wind power plants to the utility grid. Therefore, the following subsections outline the main grid code requirements.

A. GENERAL REQUIREMENT OF GRID CODES

It is expected that wind power plants should operate continuously with grid frequency variations in the range (49.5 − −50.5)Hz. Reference [24] presents a detailed study of requirements defined by grid codes, which help the wind turbines to participate in frequency control and synthetic inertia. As well a study on frequency support methods by wind power plants is reported in [25]. Reference [26] contributes a detailed analysis to investigate the effects of frequency sensitive wind power plants on control of load frequency in the hybrid power system. A comparative study of frequency limits adopted by the various countries as per international grid codes is detailed in Table 1 [27].

Moreover, the wind generators are expected to operate within a predefined voltage variation range. Continuous voltage range between 0.9 to 1.1 pu is adopted by most of the countries. Voltage fluctuations range of ±5% is maintained in most of the countries for pre-fault or pre-disturbance. However, this voltage range depends on the actual system voltage level. Australian grid codes define that wind power plants (WPPs) must operate within the voltage range of 90-110% [28]. According to Egypt grid codes, the wind power plant should deliver active power when voltage remains within ranges as detailed in Table 2 [29]. As per Indian electricity grid codes (IEGC), wind turbines remains connected to the grid and produce power for voltage ranges specified in Table 3 [30].

TABLE 1. Frequency limits defined in international grid codes for various countries.

Country	Frequency limit (Hz)	Maximum duration
Australia	49.5 < f < 50.5	Continuous
	49.0 < f < 51.0	10 min.
	48.0 < f < 51.0	2 min.
	47.5 < f < 52.0	9 s
Canada	59.4 < f < 60.6	Continuous
	58.5 < f < 61.5	11 min.
	57.5 < f < 61.7	1.5 min.
	57.0 < f < 61.7	10 s
	56.5 < f < 61.7	2 s
	55.5 < f < 61.7	0.35 s
Denmark	48.5 < f < 51.0	Continuous
	48.0 < f < 51.0	25 min.
	47.5 < f < 52.0	5 min.
	47.0 < f < 52.0	10 s
Germany	49.0 < f < 50.5	Continuous
	48.5 < f < 51.5	30 min.
	47.5 < f < 51.5	10 min.
	46.5 < f < 53.5	10 s
India	49.5 < f < 50.5	Continuous
	47.5 < f < 51.5	WPP remains connected
Ireland	49.5 < f < 50.5	Continuous
	47.5 < f < 52.0	60 min.
	47.0 < f < 52.0	20 s
United Kingdom	47.5 < f < 52.0	Continuous
	47.0 < f < 52.0	20 s
United States of America	60.0 < f < 59.5	Continuous
	59.5 < f < 59.3	10 min.
	59.3 < f < 58.7	10 s

TABLE 2. Minimum operational time period of wind power plant: Egypt grid codes.

Voltage Range	Time period of operation
0.85-0.90 pu	Unlimited (Continuous operation)
0.90-1.10 pu	Unlimited (Continuous operation)
1.10-1.15 pu	30 min.

TABLE 3. Grid voltage operating limits: IEGC.

Nominal system voltage	Voltage level		
	Voltage variation limits	Maximum	Minimum
400 kV	+5%/-10%	420 kV	360 kV
220 kV	±10%	245 kV	200 kV
132 kV	±10%	145 kV	120 kV
33 kV	±10%	36 kV	30 kV

Wind power plants are expected to deliver sufficient reactive power to meet local interconnection issues and provide voltage regulation services to the transmission system operator. Typical power factor range is 0.9 inductive to 0.98 capacitive [31]. It is required for the wind power plant to operate within power factor limits of 0.95 C to 0.95 L when wind generation constitutes more than 20% of rated power. A comparative study of operating ranges of power factor in international grid codes for which WPPs are enforced to remain connected and deliver power is specified in Table 4 [32].

International grid codes specify that WPPs must control their active power to provide frequency regulation facility to the transmission system operator. However, the wind generators are exempted from the increase in active power to

TABLE 4. Limits of power factor: International grid codes.

Country	Power factor	
	Capacitive	Inductive
Australia	0.930	0.930
Canada	0.900	0.950
Denmark	0.950	0.950
Germany	0.950	0.925
Ireland	0.950	0.950
New Zealand	0.950	0.950
Spain	0.910	0.910
United Kingdom	0.950	0.950
United states of America	0.950	0.950

maintain frequency drop. Output active power of the wind generators must be curtailed to control the rise in frequency to help in maintaining a balance between generation and consumption of wind power [33]. Reference [34] presents a study on active power dispatch solution for the utility grids in the presence of large scale integration of wind energy.

B. LVRT CAPABILITY REQUIREMENT OF GRID CODES

The most crucial requirement of revised international grid codes is low voltage ride through (LVRT) capability of wind generators. LVRT is also called fault ride through (FRT). This phenomenon indicates the capability of the large wind farms for staying connected for a short time during events of fault and voltage dip [35]. This ensures that for usually cleared faults there is no loss of wind generation. The utilities also require that wind generators support the grid during faulty events and these generators must be able to withstand dips in voltage for specified periods. Voltage versus time characteristic curves are used to describe LVRT requirements which also denotes minimum immunity of wind power plants to voltage sags. Fig. 5 illustrates a combined LVRT profile of wind power plants based on the combination of LVRT requirements in various countries. Disconnection of the wind power plant is not allowed above the borderline and required to contribute power to the utility grid whereas these plants can be disconnected from the grid below the borderline. For a fault duration of 1.5s and below solid line, the wind power plant may be

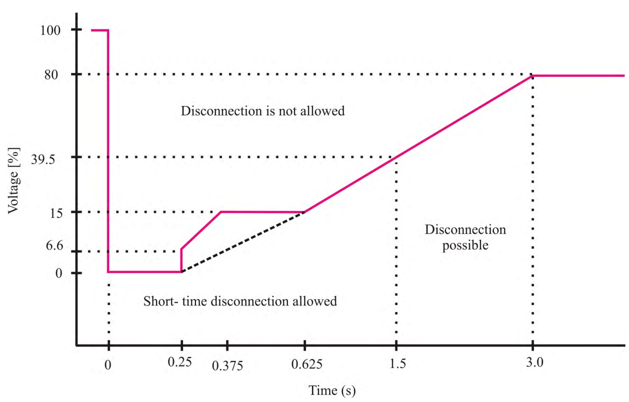

FIGURE 5. A combined profile of LVRT requirements for wind power plants based on grid codes of different countries.

TABLE 5. LVRT requirements: International grid codes.

Country	During faulty condition		After fault clearance	
	$V_{min}(pu)$	$T_{max}(s)$	$V_{min}(pu)$	$T_{max}(s)$
Australia	0.00	0.10	0.70	2.00
Canada	0.00	0.15	0.85	1.00
Denmark	0.20	0.50	0.90	1.50
Germany	0.00	0.15	0.90	1.50
Canada	0.00	0.15	0.85	1.00
India	0.15	0.30	0.85	3.00
Ireland	0.15	0.625	0.90	3.00
New Zealand	0.00	0.20	0.60	1.00
Spain	0.00	0.15	0.85	1.00
United Kingdom	0.15	0.14	0.80	1.21
USA (FERC)	0.15	0.625	0.90	3.00
USA (WECC)	0.00	0.15	0.90	1.75

disconnected for short duration if it can be resynchronized to the grid within 2s. If voltage persists below 40% of the normal value for a period higher than 1.5s, the wind power plant may be disconnected unconditionally [36]. An analysis of the effectiveness of LVRT techniques used for doubly fed induction generator (DFIG) and various control techniques are reported in [37]. Reference [38] proposes a technique for assessment of voltage quality while considering LVRT requirements of wind generators. A comparative study of LVRT requirements in different countries is provided in Table 5. Table 6 presents the comparative study of various standards utilized for grid integration of wind power plants and LVRT capability of wind systems. Also, the comparative study of LVRT techniques of wind turbines in terms of commonly used grid codes is listed in Table 7 in detail.

C. HIGH VOLTAGE RIDE THROUGH CAPABILITY REQUIREMENT OF GRID CODES

Recently, some of the countries have also included voltage-time profiles for conditions of swells in voltage in the grid codes. Voltage swells may be initiated by energizing capacitor banks, switching off the large loads and occurrence of faults. This requirement is referred to as the high voltage ride through (HVRT) capability. Fig. 6 illustrates curve which describes HVRT requirements of Australian grid codes [32]. Reference [39] proposes a dynamic reactive power based HVRT control strategy of DFIG wind turbine.

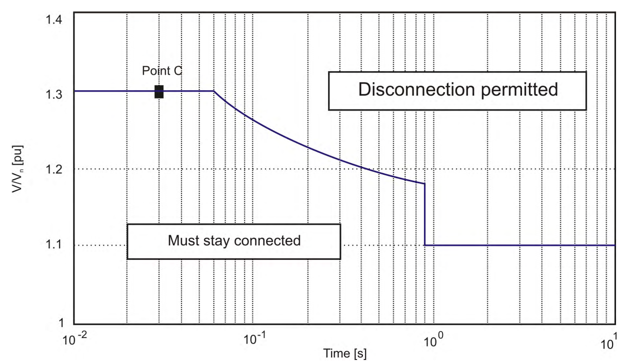

FIGURE 6. HVRT requirement: Australian grid codes.

TABLE 6. International standards used for grid integration of wind power plants and LVRT capability.

Standard Code	Description of the standard
IEEE 1547.4^{TM}-2011	This standard specifies different methods for interconnection and operation of distributed resources with the utility grid. It also specifies how distributed resources can disconnect and reconnect with utility power while supplying power to the grid.
IEEE 1547.4^{TM}-2013	Impacts and other engineering aspects of integrating distributed generation system with national grid have been discussed in this standard.
IEEE 1668^{TM}-2014	This standard defines examination methods for testing the electrical equipment's low voltage ride through performance connected to low voltage networks especially for voltage dips persisting for within a minute.
IEC 60050-415, IEC 61400-1	These standards define design safety and operational conditions of wind turbines under different circumstances.
IEC 61400-27	This standard specifies generic and dynamic models of wind turbine generation to improve stability of the power system.
IEC 62477-1	This standard is applied as a directory for safety provisions of power electronic converters based renewable energy (RE) systems.
IEC 61508	This standard specifies functional safety of electronic converters.
IEC 61400-21	This standard outlines the measurements and assessment procedures for power quality testing of wind generators. It also stipulates testing procedures for LVRT capability of WECS.
ANSI/IEEE 1021-1988	This standard specifies the recommended method for the integration of wind turbines with national grids.

TABLE 7. LVRT specifications of wind power plants: Commonly used grid codes.

Grid Code	Description
Brazilian Grid Code	Wind power plant is expected to maintain a grid connection for a duration of 500 ms when the voltage drops to 20%. These plants should be able to recover 85% of nominal voltage within 1 s and maintain this voltage for a duration of 4 s. These plants should be capable of recovering 90% of system voltage within 5 s duration.
German Grid code	Wind power plant shall not be disconnected from utility grid if the voltage at PCC remains above Limit Line 1. These generators may be detached between Limit Lines 1 and 2 for some hundred milliseconds. The generator is allowed to trip for voltages below Limit Line 2.
Chinese Grid Code	The wind generator shall not be disconnected from the grid for a duration of 625 ms if the terminal voltage is below 20%. The wind power plant shall recover 90% of terminal voltage within 3 s.
Spanish Grid Code	The wind generator shall not be disconnected from the grid for the duration of 500 ms if the voltage at PCC is under 20%. The wind power plant shall recover 80% of terminal voltage within 1 s.
Denmark Grid Code	The wind generator shall not be disconnected from the grid for the duration of 100 ms if the system voltage is under 20%. The wind power plant shall recover 75% of system voltage within 750 ms.
Italian Grid Code	The wind generator shall not be disconnected from the grid for the duration of 500 ms if the system voltage is under 20%. The wind power plant shall recover 75% of system voltage within 750 ms.
Sweden Grid Code ($<$ 100 MW)	The wind generator shall not be disconnected from the grid for a duration of 250 ms if the system voltage is below 25%. The wind power must be capable of supplying 90% of rated voltage within 250 ms.
Sweden Grid Code (>100 MW)	The wind generator shall not be disconnected from the grid for the duration of 250 ms if system voltage drops to zero. The wind power plant shall recover 90% of system voltage within 750 ms.

Superconducting magnetic energy storage (SMES) based HVRT method for DFIG based wind turbine is reported in [40]. Reference [41] proposes a resonant controller based HVRT control method for DFIG wind turbine. Table 8 presentes a comparative study of HVRT requirements according to the international grid codes.

TABLE 8. HVRT requirements: International grid codes.

Country	During Voltage Swell	
	$V_{max}(pu)$	$T_{max}(s)$
Australia	1.3	0.06
Denmark	1.2	0.1
Germany	1.2	0.1
Spain	1.3	0.25
USA	1.2	1

IV. LVRT SCHEMES OF WIND ENERGY CONVERSION SYSTEMS

Different methods have reported in the literature for LVRT capability of different types of wind generators. In the recent years, three types of wind turbine generator systems are generally in use for wind power production: (1) fixed speed wind turbines (FSWT) which use SCIG, (2) variable speed wind turbines (VSWT) using DFIG and (3) VSWT using PMSG [7]. As structures, generator technologies and control methods are different for various types of existing wind turbines; hence they require different methods to enhance

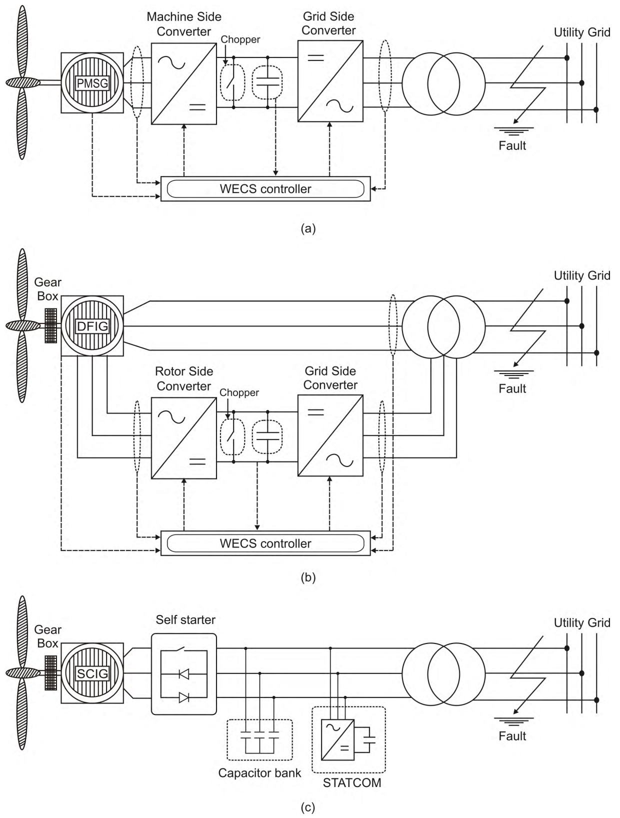

FIGURE 7. Wind energy conversion system using (a) PMSG wind turbine and chopper circuit based LVRT scheme (b) DFIG wind turbine and chopper circuit based LVRT scheme (c) SCIG wind turbine and STATCOM based LVRT scheme.

the LVRT capabilities. Fig. 7 (a), illustrates configuration of a WECS using PMSG. This figure also illustrates back to back full-scale pulse width modulation (PWM) voltage converter, three-phase fault location and LVRT scheme using chopper circuit. Fig. 7 (b), describes the configuration of a WECS using DFIG. Three-phase stator winding is directly connected to the utility grid whereas three phase rotor winding is connected to the rotor side converter (RSC) and grid side converter (GSC). This figure also illustrates the location of the three-phase fault and LVRT scheme using the chopper circuit. Fig. 7 (c), details configuration of a wind energy conversion system using SCIG. A capacitor bank is used to provide reactive power compensation during the steady-state operation. A soft starter is used to connect and disconnect SCIG to/from the utility grid. Location of the three-phase fault and LVRT scheme using STATCOM is illustrated as well in this figure [42].

An algorithm using power management technique has reported in [43], which is useful in keeping wind turbine generator (WTG) connected to the utility grid during the faulty condition, but disconnects WTG if the fault persists. To provide a high-quality power profile and to smooth wind power fluctuations, a super-capacitor is used to store the energy while riding through a grid fault. Espinoza *et al.* [44], proposes a piece of equipment using voltage source converter (VSC) for LVRT testing method of wind turbines. The investigated method can be used for every type of renewable source. Reference [45] reports a control technique for an offshore wind power plant using VSC-HVDC transmission with increased LVRT capability during fault conditions of symmetrical and unsymmetrical. In Reference [46], authors proposed a self-tuning resonant control method for LVRT control of wind energy conversion system during symmetrical and unsymmetrical faults. This method has advantages of operation of the wide frequency range. Tahir *et al.* [47] have proposed a method using positive grid voltages extracted using phase-locked loop (PLL) and high selectivity filter (HSF) to increase the LVRT capability of the wound field synchronous generator (WFSG) based wind turbines. This method has advantages that it works effectively in the balanced supply voltages, distorted and unbalanced conditions. Reference [48] proposes a modulation method for wind power converter using neutral point clamping to achieve thermal reduction and loss minimization under LVRT operation. A comparative study of LVRT capability with the detailed mathematical design of single rotor wind turbine (SRWT) and dual-rotor wind turbine (DRWT) is presented in [49]. The next sections present a detailed study of LVRT methods used for DFIG, PMSG, and SCIG with their merits and demerits.

V. LVRT METHODS FOR DFIG WIND TURBINES

Recently, the DFIG is the most widely applied electrical generator for wind power applications because it has advantages of operation with speed variability while the frequency kept fixed. Decoupled control of active and reactive powers, as well as the use of partial scale converters (25-30% of system rating), are additional advantages. It has disadvantages of high vulnerability to grid disturbances, especially grid faults, due to direct integration of stator winding of DFIG to the grid. Voltage sags due to faults on the stator terminals cause rotor overcurrents, oscillations of torque and DC link overvoltages and may cause damage to mechanical parts, DC-link capacitor, and RSC. Hence, proper control technique and protective measures are required for DFIG to stay connected to the utility network during faulty events [50]. Hence, LVRT approaches are mainly required for the DFIG to remain connected during faulty events. These methods can be divided broadly into two categories. The first category includes hardware modification and the second category includes modifications in conventional converters of the DFIG. Hardware-based LVRT schemes are further divided into two categories: one using protection circuits and others using reactive power injecting devices. Fig. 8 provides classifications of various types of LVRT schemes of DFIG-based wind power plants. To provide LVRT capability to the DFIG based wind turbine, Table 9 [51] provides a comparative study of hardware modifications and conventional converter modifications. The subsequent section describes some of the commonly used LVRT schemes of the DFIG.

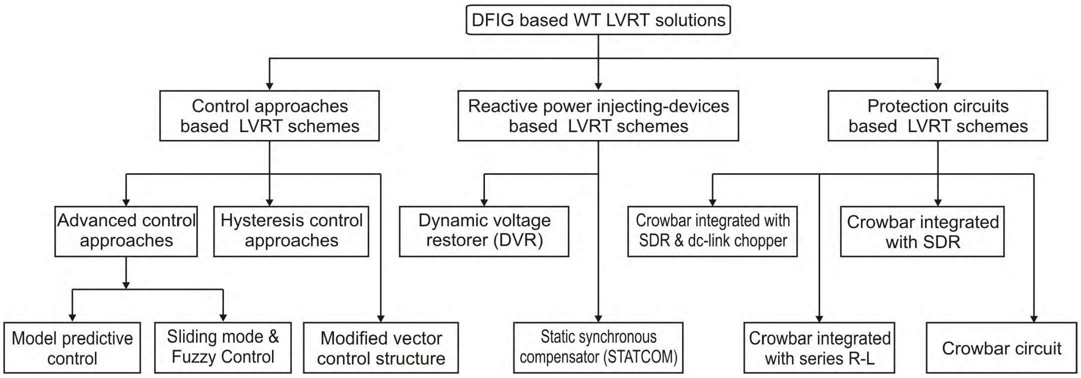

FIGURE 8. LVRT schemes of wind power plants based on DFIG.

TABLE 9. Advantages and disadvantages of strategies used to improve LVRT capability of DFIG.

LVRT Strategy	Advantages	Disadvantages
Hardware modification	1) This method helps to decrease DC-link over voltage, torque oscillations, and rotor over current 2) Effective under both symmetrical and unsymmetrical grid faults 3) This methodology is efficient under deep voltage sags	1) Extra hardware is needed 2) The complexity and cost of the system increases 3) Decrement of the system reliability
Modifications in converter control	1) This method helps to decrease torque oscillations, rotor over current and DC-link overvoltage 2) Extra hardware is not required 3) System complexity and cost does not increases 4) Reliability of the system is not decreased	1) This methodology is serviceable just in the situations of moderate voltage sags 2) Often useful under symmetrical grid faults

A. LVRT CAPABILITY USING CROWBAR PROTECTION

Most known LVRT approach for the DFIG based wind turbine (WT) is the use of the crowbar (CB) protection circuit. Current crowbar circuit is an electrical circuit designed by resistors and connected across rotor winding terminals [52]. Fig. 9 illustrates the arrangement of a crowbar fault protection system of DFIG. Working of the crowbar protection using resistance for LVRT improvement can be understood by the configuration shown in Fig. 10 (a). It comprises a collection of power electronic devices for connection to a set of resistors to slip rings at rotor side to circumvent the RSC. During the fault event, a high magnitude rotor current transient is generated because of DFIG rotor and stator magnetic couple. Hence, for protection of power converters, a resistor bank known as crowbar protection is deployed for short-circuiting the RSC. Value of crowbar resistance depends on generator design data. It limits rotor current during the faulty event. By activation of crowbar, RSC is disabled and active and reactive powers will be independently controllable. In this condition, generator magnetization is over the stator, and the DFIG starts acting as a SCIG and absorbs reactive power from grid network which helps to increase dip in voltage. Once safe operation of RSC is detected, crowbar protection is deactivated, and normal operation of the RSC is resumed. High resistance on the rotor due to crowbar protection may generate high voltage enough to damage the RSC switches [53]. Optimal value of crowbar resistance ($R_{crw-opt}$) is given by following relation [54].

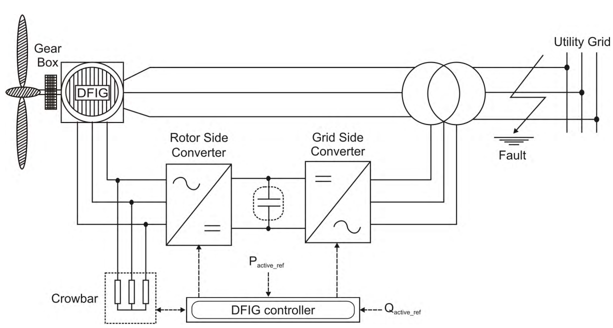

FIGURE 9. Protection arrangement of the crowbar for LVRT capability improvement of DFIG.

$$R_{crw-opt} = \frac{\sqrt{2}(V_{rmax}\omega_s L_s)}{\sqrt{(3.2V_s^2 - 2V_{rmax}^2)}} \tag{7}$$

where ω_s is synchronous speed; V_{rmax} is maximum rotor voltage; V_s is stator voltage; L_s is stator inductance.

TABLE 10. Comparison of different crowbar protection circuits for LVRT improvements of DFIG.

LVRT method	Limit of rotor current (pu)	Status of rotor-RSC connection	Limit of DC-link voltage (pu)	Comment	References
Crowbar circuit with R only	< 2.0	Blocked	< 1.35	Effective for symmetrical faults only	[54]
Crowbar circuit with RL	< 2.4	Maintained partially	< 1.35	Effective for all types of faults	[55]
Crowbar circuit with Chopper	< 2.4	Blocked	< 1.35	Effective for all types of faults	[62]
Crowbar circuit with DVR	< 2.0	Maintained partially	< 1.25	Effective for all types of faults	
Crowbar circuit with DSR	< 2.0	Maintained partially	< 1.35	Effective for all types of faults	[54]
Active crowbar circuit	< 2.0	Maintained partially	< 1.08	Effective for all types of faults	[59]

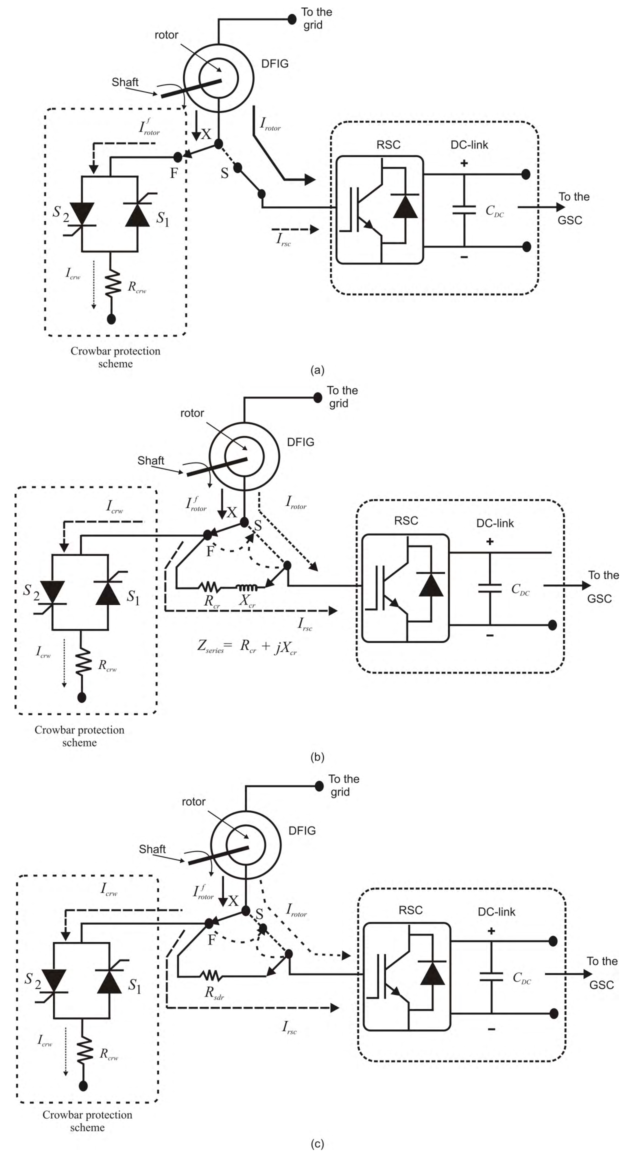

FIGURE 10. Crowbar protection for LVRT capability improvement of DFIG (a) the principle of working (b) joined with RL protection circuit (c) joined with series dynamic resistor.

Fig. 10 (b) shows an enhanced circuit designed by combining the resistance crowbar and a series RL circuit to overcome the opposing effects of resistance crowbar circuit, [55]. The installation of this circuit exists between rotor windings and ac side terminals of the RSC connected to the rotor winding through a series RL branch during the fault event. During the disturbance, the rotor is protected from high inrush currents by bypassing rotor current through a proposed circuit connected between rotor winding terminals and the ac side of the RSC [56].

Yang *et al.* [54], proposes a crowbar protection scheme in coordination with dynamic series resistance (DSR) as shown in Fig. 10 (c). In normal operational mode, the DSR switch is closed and bypasses the series resistance. During fault event for increasing rotor current above maximum allowable limit of RSC, the DSR inserted in series with rotor circuit operates to limit rotor current [57]. The DSR helps to maintain inrush current of rotor and DC-link over voltage within predefined threshold values. This also helps to maintain the RSC connection to the rotor windings which results that the generator control is not lost. Hence, original features of the DFIG based WECS system are maintained.

Literature details the various modifications in the crowbar protection system of the DFIG. Reference [58] presents an enhanced crowbar protection design utilizing a capacitor cascaded by the resistor. Capacitor improves the stator terminal power aspects of the DFIG in the time period of crowbar fired by supplying reactive power. A crowbar circuit uses devices such as IGBT, GTO, transistor or forced commutated thyristors for switching purpose. Active crowbar ensures short circuit during the transient period and resumption of routine operation when a transient is over. Ref. [59] proposes an active crowbar circuit using a capacitor, resistor and IGBT switch for improvement of LVRT capability of the DFIG. Reference [60] proposes active crowbar protection based on the silicon control rectifier (SCR) for LVRT improvement of the DFIG where circuit mainly consists of delta connected SCRs configuration and resistors to dissipate transient energy. Reference [61] reports a practical approach for the calculation of crowbar resistance to provide useful LVRT capability to brushless DFIG. Moreover, Table 10 provides a comparative study of various crowbar circuits for LVRT improvement of DFIG.

B. LVRT CAPABILITY USING STATOR DAMPING RESISTORS

In this method, passive resistive hardware, called stator damping resistor (SDR) is in cascaded connection to stator winding of DFIG. It comprises connection of three resistors parallel with bidirectional static bypass switch as shown

TABLE 11. Performance of DVR for LVRT improvements of DFIG.

Type of fault	Voltage sag	Three phase load voltage during fault without LVRT			Three phase load voltage during fault with LVRT		
		R	Y	B	R	Y	B
Three-phase to ground fault	100%	0.108	0.112	0.109	1.006	0.998	1.002
	50%	0.423	0.425	0.423	1.008	1.002	1.003
Double line to ground fault	100%	1.040	0.107	0.108	1.005	1.001	1.002
	50%	1.039	0.413	0.409	1.007	1.002	0.998
Single phase to ground fault	100%	1.041	0.108	1.044	1.006	1.002	1.003
	50%	1.042	0.409	1.043	1.002	1.007	0.999

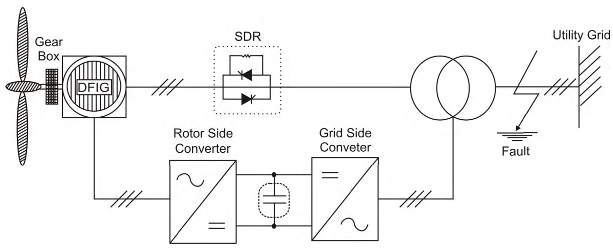

FIGURE 11. Stator damping resistor for LVRT improvement of DFIG.

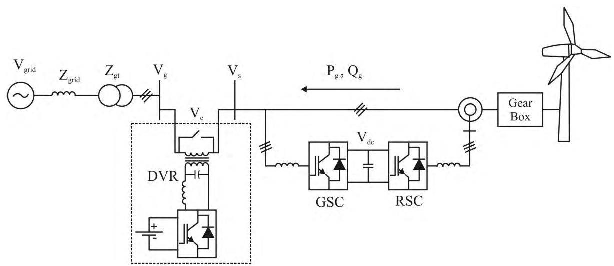

FIGURE 12. Dynamic voltage restorer based scheme for LVRT improvement of DFIG.

in Fig. 11 [63]. In regular operation, the switches are closed and the current flows through the SDR. In the case of a faulty event, switches are open and the current will flow through SDR resistors limiting stator current. Hence, SDR is capable of enhancing the LVRT capability based on DFIG in a wind power plant [64]. Reference [65] reports a dynamic resistor cascaded with the stator winding along with a controller of nonlinear nature. A passive network using series impedance and connected on the stator side of a wind turbine based on DFIG is detailed in [66]. The reported method has low maintenance and manufacturing cost, and it is easy to control. Moreover, it has high efficiency and capable of off-line operation.

C. LVRT CAPABILITY USING DC LINK CHOPPER

During faulty events, the voltage of DC-link may rise above maximum permissible limits. This may result in damage to the DC-link capacitor as well as power electronic switches. The solution to this problem is by using a chopper circuit cascaded to the DC-link capacitor as illustrated in Fig. 7 (b). Chopper circuit shorts DC-link capacitor with the help of a power resistor when the voltage exceeds the predefined maximum value. Surplus available active power will be dissipated in a resistor of chopper circuit during faulty events [67], [68]. Reference [69] presents an experimental study of an LVRT method by application of a brake chopper circuit connected in parallel with DC-link of DFIG to control dc-link voltage in a fault event.

D. LVRT CAPABILITY USING DYNAMIC VOLTAGE RESTORER

Dynamic voltage restorer (DVR) is made of a voltage source converter (VSC) connected in series in the line between DFIG and grid, and it improves the LVRT capability of DFIG. DVR is capable of compensating for voltage swell, sag, and harmonics, and it is very much sufficient for voltage sag compensations in LVRT applications of DFIG. Fig. 12 illustrates that DVR is installed at PCC for injection of voltage in series to provide compensation of active and reactive power in the grid which helps to recover from faults [70]. Rating of DVR depends on the fault voltage magnitude to be compensated. The following relation gives active power of DVR (P_{DVR}) required for voltage sags and swells with a zero-phase angle jump.

$$P_{DVR} = \left(\frac{V_{pcc} - V_f}{V_{pcc}}\right) \times P_{load} \tag{8}$$

where V_{pcc} is voltage on PCC, V_f is voltage on terminals of VSC of DVR, P_{load} is active power consumed by load.

Reference [71] exhibits a detailed comparative study of system topologies of DVR. A method for improving a DFIG capability of LVRT in wind turbine system using a DVR has been demonstrated in [72]. Also, Reference [73] shows an approach using supercapacitor energy storage system (SCESS) and DVR for LVRT capability of DFIG in both symmetrical and unsymmetrical faults. A detailed study of DVR to improve voltage unbalance levels of the grid by controlling the wind turbine is manifested in [74]. Reference [75] proposes a DFIG based WECS improved LVRT capability using customized dynamic voltage restorer. Table 11 provides the performance of prescribed DVR for compensation of voltage sags during faulty events. It is observed that the proposed approach is highly useful to improve the LVRT capability of DFIG. According to national electrical manufacturers association (NEMA), below is the voltage unbalance factor (VUF).

$$VUF(\%) = \frac{V_2}{V_1} \times 100 \quad (9)$$

where V_1 is a positive sequence voltage and V_2 is negative sequence voltage. Phase angle (δ) between grid voltage (V_g) and the DFIG terminal voltage (V_t) should be maintained below maximum value to avoid overloading of DVR. The following relation [76] gives the maximum value of the phase.

$$\delta_{max} = cos^{-1}\left(\frac{V_t^2 + V_g^2 - V_{c(max)}^2}{2V_gV_t}\right) \quad (10)$$

Where V_{cmax} is maximum DVR compensating voltage. Table 12 provides a cost comparison of various hardware protection devices used for LVRT improvement of wind turbine based on DFIG.

TABLE 12. Cost comparison of hardware based LVRT improvement schemes of DFIG wind turbine.

S. No.	Hardware LVRT Scheme	Price (US$)
1	Classical DVR	67,229.99
2	Low cost DVR	36,778.79
3	STATCOM	200,000.00
4	Active crowbar protection	85.00

E. LVRT CAPABILITY USING MODIFICATIONS IN CONTROL OF THE CONVERTER

Control approaches used for the control of RSC and GSC also affect the performance of LVRT strategies. Proper tuning of the controllers also affects LVRT capability of the DFIG [77]. Table 13 renders different control approaches reported in the literature for improvement of the DFIG capability of wind power plants based on LVRT.

F. IMPROVED LVRT METHODS

In recent years enhanced LVRT methods for DFIG based wind turbines have been presented which provide cost-effective solutions. Reference [98] proposes an inductance emulating control method for suppressing post-fault rotor current to improve the capability of LVRT in the wind turbine based on DFIG. Extremum value of emulated inductance effectively controls rotor voltage and post-fault current. It also suppresses electromagnetic torque oscillations during the transient state, during fault and fault recovery time periods. An evolved LVRT method for DFIG wind turbine which is working effectively during both symmetrical and unsymmetrical faults has been recognized using active and passive compensators in Reference [99]. This method is realized as effective in decrement of stator and rotor over-currents during fault occurrence and clearance periods. Reference [100] manifest the LVRT control method for DFIG wind turbine based virtual damping flux. It is useful in suppressing rotor current associated with smooth electromagnetic torque during the transient state of drop and recovery of grid voltage. Reference [101] presents a time domain analysis of coordination between rotor current and voltage which helps to ride through grid fault with the limited capacity of RSC. In Reference [102], authors propose an LVRT control method for DFIG wind turbine using the conventional current loop and an additional flux loop which is sufficient to control active power and reactive power. This scheme is capable of decaying stator transient flux and maintaining the constant stator active power and electromagnetic torque. Reference [103] proposes a demagnetization LVRT method of DFIG wind turbine which is competent to provide ride-through at the moment of fault recovery. In Reference [104], authors present a coordinated control scheme for converters of DFIG wind turbine to provide transient reconfiguration and LVRT improvement.

G. MISCELLANEOUS LVRT IMPROVEMENT METHODS

Reference [105] details a parallel resonance bridge type fault current limiter (PRBFCL), deployed for improving the hybrid power system transient stability incorporated with DFIG based WECS, the solar PV system and the synchronous generator (SG). Reference [106] proposes a model of DFIG with complete LVRT process considering post-fault power recovery behavior of the DFIG. Reference [107] reports an approach using DC-link switch-able resistive type fault current limiter (SRFCL) to enhance the LVRT capability of DFIG. Reference [108] proposes a control strategy to improve LVRT of DFIG during balance grid faults and a hardware solution for unbalanced faults. This method reduces negative impacts of grid faults on the DFIG by decreasing electromagnetic torque, damping stator power oscillations and canceling stator and rotor over-currents. In Reference [109], authors propose a method to improve LVRT of DFIG based wind turbine using a gate controlled series capacitor (GCSC) connected in series with rotor circuit. This method deals with electromotive forces (EMFs) induced during grid faults to enhance LVRT. Table 14 frames a comparative study of the GCSC method with the crowbar method. A simple controller based resistive type solid-state fault current limiter (SSFCL) to enhance the LVRT in the wind turbine based on DFIG transient stability as offered in Reference [110]. Reference [111] proposes a brushless DFIG with improved LVRT capability and reliability. Reference [112] proposes an LVRT scheme of DFIG based wind turbine comprises one uncontrolled rectifier, an inductor, a diode, and two sets of IGBT switches. This composition breathes between the rotor circuit and DC-link capacitor in parallel with the rotor side converter – this strategy stored mechanical energy of wind turbine during fault and utilizes the same in fault clearance duration. A lookup table based approach for LVRT capability enhancement of wind turbines based DFIG reported in Reference [113]. An LVRT method for wind turbine based on DFIG using fault detection and identification (FDI) based on artificial neural network (ANN) as published in Reference [114]. An LVRT scheme employing a resistive type superconducting fault

TABLE 13. Control strategies for LVRT improvements wind power plant based on DFIG.

S. No.	Control solution to improve LVRT capability	Reference
1.	Demagnetization current controller (DCC) to improve LVRT for transient stability conditions	[78]
2.	Scaled current tracking control for RSC to improve LVRT capacity without flux observation	[79]
3.	Sensor less vector control method to improve LVRT and voltage sags. Sliding mode observer (SMO) is used for estimation of rotor position and speed required for vector control of DFIG	[80]
4.	A feed-forward transient current control approach based on state estimation technique. This method minimizes transient rotor current during and after fault clearance, minimizes effect of probable noise level in metering devices	[81]
5.	Advanced vector control method to improve capability of LVRT in wind power plant based on DFIG. Active power and stator voltage control loops are on d-axis and q-axis respectively. An effective input signal (EIS) based on Lyapunov theory is added on d-axis of rotor voltage.	[82]
6.	Robust variable structure system control. It is used to design LVRT supplementary control of DFIG with objective to maximize wind energy conversion and termial voltage regulation.	[83]
7.	technique of Enhance field oriented control (EFOC) to improve LVRT capability of DFIG. It was implemented on RSC to enhance power flow transfer, transient and dynamic stability.	[84]
8.	A parallel resonance based fuzzy logic controller to limit the fault current to improve wind farm based on LVRT capability of DFIG	[85]
9.	A non-linear controller for bridge type fault current limiter for improvement of transient stability and LVRT capability of DFIG based wind farm of capacity 20 MW.	[86]
10.	A fuzzy logic second order integral terminal sliding mode control (FSOITSMC) for both GSC and RSC to improve LVRT capability of DFIG which is effective for symmetrical and unsymmetrical faults	[87]
11.	Adaptive internal model controller (AIMC) with mechanism of variable gain adjustment for LVRT improvement of DFIG based wind farm.	[88]
12.	Feed forward current reference control (FCRC) for RSC to improve LVRT capability of DFIG and transient system control performance	[89]
13.	Direct model predictive control	[90]
14.	Improve adaptive internal model controller. It is designed with mechanisms like Lyapunov theory, Fuzzy logic and artificial neural fuzzy inference system (ANFIS) to improve LVRT capability of DFIG wind power plant.	[91]
15.	Hybrid control scheme implemented in RSC and GSC of DFIG to improve low and high voltage ride through capabilities of DFIG based wind farm	[92]
16.	Proportional integral (PI) controller with modified feed-forward compensator (MFFC)	[93]
17.	A computational intelligence-based fuzzy controller tuned by genetic algorithm (GA)	[94]
18.	A hybrid current controller to improve LVRT capability of DFIGs and simultaneously maintaining rotor current below safety limits. This controller includes two strategies of switching: (1) standard PI current controller used for normal operating conditions (2) vector-based hysteresis current controller (with very fast transient response) used for over current protection during faulty conditions.	[95]
19.	A LVRT control strategy based on flux-linkage-tracking used to suppress short-circuit rotor current	[96]
20.	A power angle control strategy for DFIG integrated to utility network to improve transient performance during LVRT method	[97]

TABLE 14. Comparison of crowbar and GCSC methods to improve LVRT capability of DFIG during various kinds of faults.

Type of fault	Phase to ground fault		Double line to ground fault		Three phase fault involving ground	
	Crowbar	GCSC	Crowbar	GCSC	Crowbar	GCSC
Rotor current (pu)	< 2	< 2	>2	< 2	>2	< 2
DC-link voltage(pu)	< 1.15	< 1.15	>1.15	< 2	>1.15	< 2
Output active power (pu)	0.15	0.9	0.4	0	0	0.15
Output reactive power (pu)	-0.18	0.2	-0.12	-0.06	0	0.1

current limiter (SFCL) cascaded with DFIG rotor winding, introduced in Reference [115].

VI. LVRT METHODS FOR PMSG WIND TURBINES

Fig. 7 (a) shows a system of wind turbine with a permanent magnet synchronous generator (PMSG). A machine shaft is used to directly couple PMSG to the wind turbine. The stator winding of PMSG integrates to the grid via a back-to-back full-scale VSC and a transformer. The VSC has two components known as grid side converter (GSC), and machine side converter (MSC) which share a common DC-link capacitor [116]. This system has advantages of high efficiency, additional power supply for excitation of field is not required, and higher reliability as slip rings and gearbox are absent [117]. During events of grid faults, the voltage on PCC decreases. This effect results in an increasing GSC current to maintain power injected to the grid as constant. During the event of a high drop in voltage, the upper limit of

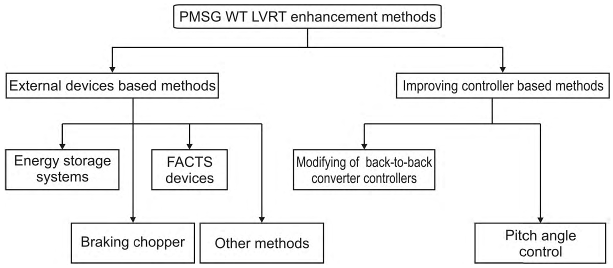

FIGURE 13. Methods for LVRT capability enhancement of PMSG based WECS.

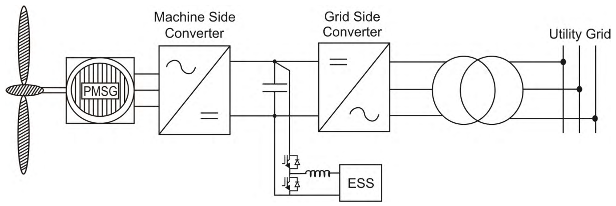

FIGURE 14. EES connected to DC-link for LVRT capability enhancement of PMSG based WECS.

the GSC current is achieved, and power injected to the grid starts decreasing. Consequently, controller of GSC cannot sense a drop in voltage at PCC and MSC continues to transfer real power to DC-link capacitor. This imbalance in real power increases the voltage of DC-link which may damage capacitor, results in generator saturation, increases voltage stress on the GSC and MSC. LVRT methods help to overcome these problems. Fig. 13 [118] presents classification of different LVRT methods used for the PMSG based wind power plants. Some of the commonly used LVRT capability methods of PMSG based WECS are detailed in following subsections.

A. ENERGY STORAGE SYSTEMS BASED LVRT METHODS

This system is external devices based LVRT improvement technique. Energy storage system (ESS) connects with the DC-link capacitor with the help of buck-boost converter for LVRT enhancement as shown in Fig. 14 [119]. During the faulty event, absorption of the additional energy of DC-link by ESS prevents the overvoltage of the DC-link. Stored energy supply to the grid network after clearance of fault which improves LVRT capability of the PMSG based WECS. Commonly used energy storage systems for improvement of LVRT capability include battery energy storage system (BESS), flow battery energy storage system (FBESS), electrical double layer capacitor (EDLC), flywheel energy storage system (FESS) and superconducting magnetic energy storage (SMES) [120].

Commonly used BESS for LVRT applications with PMSG based WECS include sodium-sulfur (NaS), lead-acid, lithium-ion and Nickel-cadmium. Flow BESS has the advantage that this is capable of discharging fully without any damage. Commonly used FBESS for LVRT applications include poly-sulfide bromide battery (PSB), zinc bromide battery (ZBB) and vanadium redox battery (VRB) [121]. Table 15 has a detailed comparative study of energy storage systems used for LVRT improvements of PMSG based WECS.

FESS is an electromechanical system which can store energy in the form of kinetic energy. Working of FESS is based on a mass coupled to electrical machine and rotating on magnetic bearings reducing friction at high speed. The complete arrangement last in a vacuum which reduces wind shear. In motoring mode of the machine, energy transfers to the flywheel. Flywheel accelerates and charges energy storage device. In regenerating mode of the electric machine through the drive, the flywheel slows down, and the system gets discharged. Energy stored by the flywheel depends on rotating speed and its inertia [122]. The following relation gives kinetic energy (E_c) stored by FESS.

$$E_c = \frac{1}{2} I \omega^2 \tag{11}$$

Where I is the inertia moment, and ω represents angular speed. Main characteristics of PMSG for which FESS can be used for LVRT capability improvement are detailed in Table 16.

Operation of the superconducting magnetic energy storage system attributes by storing energy in a magnetic coil. This coil is simulated/emulated by passing DC through a large superconducting coil at cryogenic temperature. It characterizes by the high energy storage efficiency, fast response and high controllability for power compensation [123]. Depending on operating temperature, the superconducting coil classifies as High-Temperature Coil (HTC) and Low-Temperature Coil (LTC). HTC works around a temperature of 70 K whereas LTC works around 5 K. SMES has advantages of very long cycle life and high ramp rate of power which may raise to 200 kW in short span of 20 ms [124]. An application of SMES with PMSG based WECS for mitigation of fluctuations of generated power, improvement of stability during grid faults and enhancement of LVRT capability has reported in Reference [125].

Supercapacitor (SC) is a series combination of a capacitor (C) cascaded with an equivalent series resistance (ESR). ESR ranges from 0.002 to 0.02 $m\Omega$. The supercapacitor groups into two categories: Electric double layer capacitor (EDLC) and pseudo-capacitor [126]. EDLC widely uses in LVRT applications of the PMSG based WECS. EDLC fabrication is an electrochemical concept-based technology. It stores charge through reversible absorption of ions from an electrolyte to two porous electrodes. This scheme creates an electric double layer at the electrode. Fig. 15 shows the basic working design of the EDLC. Its operation does not involve a chemical reaction, and it absorbs ion in the physical mean. A double-layer capacitor formed by solid electrode material surface separated from liquid electrolyte stores energy in micro-pores of electrodes. EDLC can last up to millions of cycles as charging and discharging process does not affect electrode physically [127]. EDLC application for LVRT capability improvement, damping of power

TABLE 15. Comparison of energy storage systems used for LVRT capability improvement of PMSG based WECS.

Energy Storage System	Discharge power range	Daily discharge (%)	Discharge efficiency	Stored energy range	Life cycle (years)
FESS	0.1-2 MW	100	0.93	0.1-60 MJ	>10
SMES	0.1-2 MW	10-15	0.95	0.1-60 MJ	>20
BESS	0.05-50 MW	0-5	0.98	0.005-50 MWh	≤ 20
FBESS	0.1-5 MW	0-3	0.98	0.005-120 MWh	≤ 20
EDLC	0-0.3 MW	5-20	0.80	0.01-120 MWh	≤ 10

TABLE 16. Characteristics of PMSG for FESS based LVRT capability.

Characteristic parameter	Parameter of PMSG suitable for LVRT
Machine power	Medium and low
Machine specific power	High($\approx$ 12 kW/kg)
Machine rotor losses	Negligible
Machine spinning losses	Non-removable, static flux
Machine efficiency	Very high(95.2%)
Machine control	Sinusoidal: vector control, Trapezoidal: DSP
Machine size	2.3l/kW
Machine Tensile strength	Low
Machine Torque ripple	Medium(10%)
Maximum/ base speed	Low($<$ 2)
Machine demagnetization	Yes

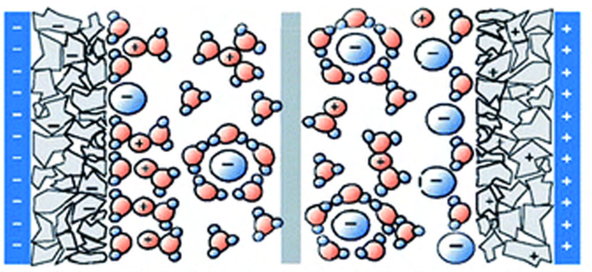

FIGURE 15. Working design of electric double layer capacitor.

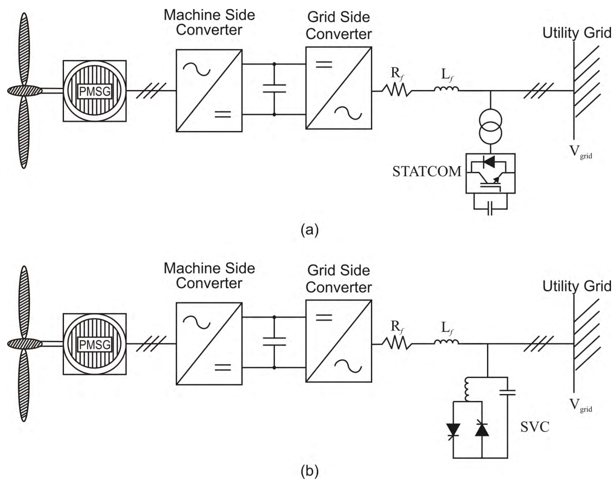

FIGURE 16. The capability of LVRT in the wind turbine based on PMSG using (a) STATCOM (b) SVC.

oscillations of short duration and extraordinary transient performance has reported in [128]. Reference [129] proposes a hybrid control scheme for EDLC and braking choppers for improvement of LVRT capability and to suppress output power fluctuations of PMSG based WECS.

B. FACTS DEVICES BASED LVRT METHODS

Flexible AC transmission system (FACTS) is modern technology which has the working capability based on the power electronic devices. It is used to meet challenges in the power industry. FACTS have been used successfully in protecting sensitive loads from voltage sag, transients and damping oscillations [130]. Recently, the FACTS devices have emerged as an effective solution to keep wind turbine systems to remain connected to the utility grid network during faulty events. These devices grouped into the three categories according to their type of connection such as series connection, shunt connection, and hybrid connection. The static synchronous compensator (STATCOM) is a device connected in the shunt. The main function of STATCOM is to supply the reactive power to the system to regulate the voltage at PCC. Fig. 16 (a), illustrates application of STATCOM for LVRT enhancement of wind turbine based on PMSG [131]. Similarly, static VAR compensator (SVC) is also a device connected in shunt which assists the improvement of the system steady state and transient performance. Fig. 16 (b), illustrates the application of SVC for LVRT enhancement of PMSG based wind turbine. Reactive power supplied by STATCOM to grid network during voltage sag is high compared to that injected by the SVC [132].

DVR is a power electronic converter based device used to protect critical loads from voltage disturbances on the supply side. This scheme is a connected series device with capability of supplying as well as absorbing both types of real and reactive powers [133]. Fig. 17 (a), illustrates the DVR for LVRT enhancement of PMSG based wind turbine. Its construction uses a transformer to connect three-phase voltage source converter in series between PCC and wind turbine [134]. In LVRT applications of PMSG, GSC is generally not capable of sensing voltage using the DVR. Design of injection transformer used with DVR for LVRT applications of PMSG differs from that of the conventional transformer.

The unified power flow controller (UPFC) is a hybrid connection topology as shown in Fig. 17 (b). The connected series component of UPFC injects voltage and compensates

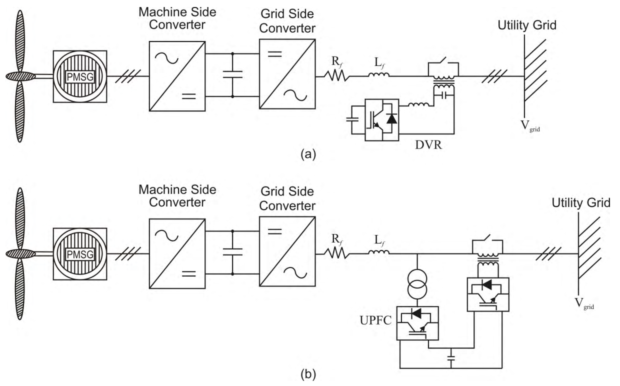

FIGURE 17. LVRT capability improvement of wind turbine based on PMSG using (a) DVR (b) UPFC.

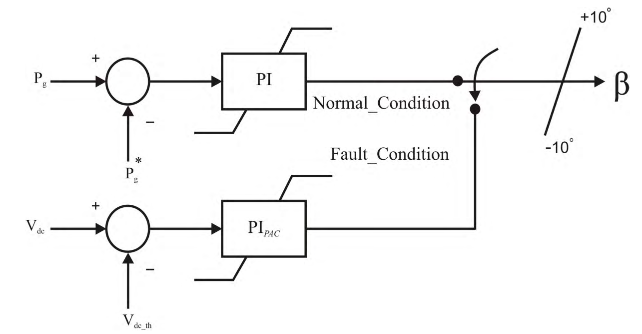

FIGURE 19. Simple pitch angle controller for LVRT capability improvement of wind turbine based on PMSG.

for voltage sags whereas the shunt component is capable of injecting reactive power into utility grid network [135]. UPFC is most effective FACTS device for LVRT applications of PMSG. However, it has a disadvantage of the high cost.

C. BRAKING CHOPPER BASED LVRT METHODS

This technique is external devices based LVRT improvement method. Braking chopper is an active crowbar circuit. It consists of a resistor of high power rating and a switch connected in parallel with DC-link of the PMSG as shown in Fig. 18. Normally IGBTs are used as switches in chopper circuit. It has advantages of the simple control structure and low-cost [136]. The duty ratio of braking chopper switch (D_{sw}) depends on the difference of generator power and sum of EDLC and grid powers (P_{BC}) as shown by following relations.

$$D_{sw} = \frac{R_{BC}}{V_{dc}^2} P_{BC} \tag{12}$$

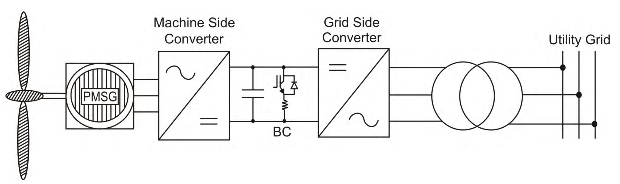

FIGURE 18. Braking chopper interfaced to DC-link of PMSG for LVRT capability improvement.

where R_{BC} is breaking resistance and V_{dc}^2 is DC-link voltage. A method for improvement of LVRT capability of PMSG which is capable of maximum power point tracking (MPPT) and reactive power management by braking chopper circuit as reported in [137]. Reference [138] proposes a strategy for control of braking chopper for improvement of LVRT capability of wind turbine based on PMSG.

D. PITCH ANGLE CONTROL BASED LVRT METHODS

This technique is a modified controller based method for LVRT improvement of PMSG based wind power plants. The mechanical output power of the pitch controlled wind turbine depends on the pitch angle (β). Pitch angle control (PAC) is normally used to limit input power during periods of gusty wind [139]. Recently, the PAC has been adopted to improve the capability of LVRT in the wind power plants based on PMSG [140]. In PAC based LVRT methods of PMSG wind turbines, the power of turbine is reduced by the pitch angle control of the turbine blade. However, the maximum rate of change in pitch angle equal to $\pm$ 10°/s and can be achieved by slow mechanical dynamics of system [141]. Fig. 19 illustrates a simple pitch angle controller for LVRT applications of wind turbine based on PMSG. For all values of wind speed above the rated value, normal control mode will remain active. However, during events of drop-in grid voltage, the PI controller which operates according to voltage variations is used to regulate the reference value of pitch angle. The PAC based method has the main disadvantage of slow response to dips in grid side voltage. The foremost benefit of this method is relatively low-cost [142].

E. MODIFIED VSC CONTROLLER BASED LVRT METHODS

This technique is the modified controller based arrangement for improvement of the capability of LVRT in the wind turbine based on PMSG. In conventional controllers, MPPT implemented by MSC and GSC is applied to control DC-link voltage. Fig. 20 (a) and (b) respectively show the conventional control strategies for MSC and GSC. The q-axis loop is applied to set MPPT and control of torque and d-axis loop is used to maintain unity power factor on generator terminals. Similarly, the GSC also has two loops. Loop of q-axis is utilized for reactive power control and providing voltage support to grid network whereas d-axis loop is used to control voltage of DC-link which helps in the injection of active power to the utility grid network [143].

Modified back to back converter based on multilevel converter topology and using carrier phase shifted sinusoidal pulse width modulation (PWM) control method to improve LVRT capability wind turbine based on PMSG as reported in Reference [144]. Reference [145] presents a model predictive control (MPC) of both MSC and GSC of PMSG to enhance LVRT capability. Three level boost converter, three-phase

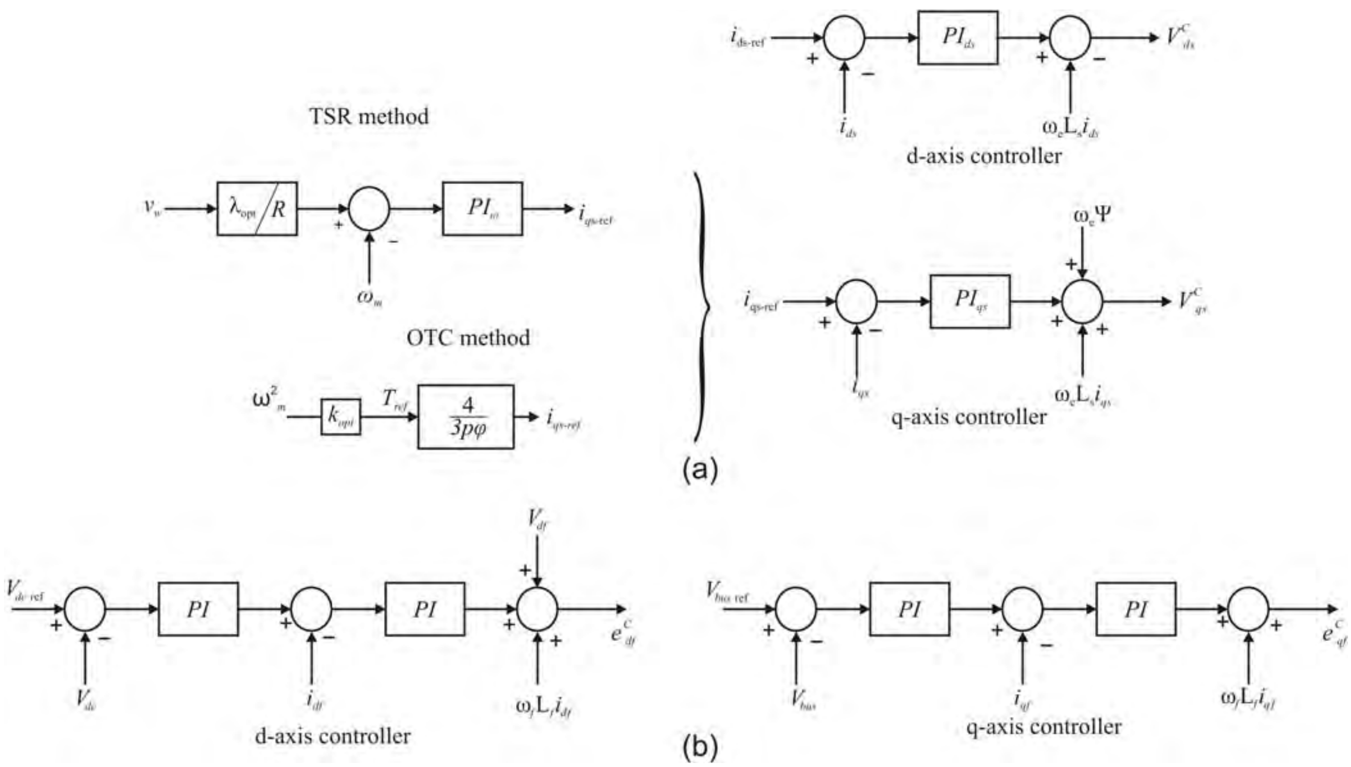

FIGURE 20. Conventional control system for (a) MSC (b) GSC.

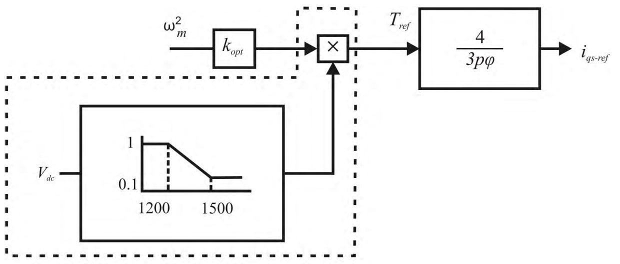

FIGURE 21. De-loading droop for LVRT improvement of PMSG-based wind turbine.

diode bridge rectifier and neutral point clamped (NPC) inverter have been used to realize power conversion system. Turbine generator inertia and converter control system based on MPC are used to improve LVRT capability. Reference [146] proposes a control mechanism based on internal model state feedback control (IMSFC) in order to eliminate *dq* current steady state error. Control is achieved using a linear quadratic regulator. In Reference [147], authors propose a de-loading droop approach for improvement of LVRT capability of PMSG wind turbine which is shown in Fig. 21. Excess power gets stored as mass kind of kinetic energy. The generator is de-loaded by multiplying de-loading droop with optimal reference torque. Reference [148] reports a flux weakening control using the concept of the proportional resonant current controller to reduce DC-link voltage of PMSG based WECS for LVRT improvement. A design of GSC of PMSG using sliding mode control (SMC) taking into consideration the non-linear relationship between generator power and voltage of DC-link satisfying LVRT capability has proposed in Reference [149]. Xing *et al.* [150], proposes a composite control method for LVRT capability enhancement of wind turbines based on PMSG. In this method surplus power during LVRT is converted into kinetic energy of rotor. This technique has achieved by controlling the electrical power of the PMSG according to the active power of the GSC. Crowbar circuit is reserved to consume surplus power before MSC reacts to grid faults. Reference [151] proposes an improved fast dynamic system for controlling matrix converter (MC) using modified hysteresis current controller and optimal tuning PI controller for LVRT improvement of PMSG based WECS. An improved bacterial foraging optimization (BFO) method is applied for controling the active and reactive current of the PMSG.

F. MISCELLANEOUS LVRT IMPROVEMENT METHODS

A series dynamic breaking resistor (SDBR) is a resistor cascaded with the PMSG and PCC as depicted in Fig. 22 (a). This scheme is kept short-circuited during a reasonable operational period and put into the circuit during a fault condition using a switch. During the faulty event, the voltage on the grid side increases due to the voltage drop along the resistor by current flowing through this resistor. Hence, energy dissipates in the SDBR which prevents overvoltage across the DC-link [152].

TABLE 17. Comparison of LVRT methods of PMSG based WECS.

LVRT Method	Relative Cost	Relative complexity	Grid code compliance		Requirement of additional device	Reference
			Dc-link over voltage	Reactive current injection		
PAC	Low	Low	Yes	Medium	Not required	[139]
EDLC	High	Medium	No	Good	Required	[128]
BC	Medium	High	No	Good	Required	[136]
DVR	Highest	Highest	No	Very Good	Required	[134]
SDBR	Medium	Medium	No	Low	Required	[152]
De-loaded loop	Low	Low	No	Medium	Not required	[147]

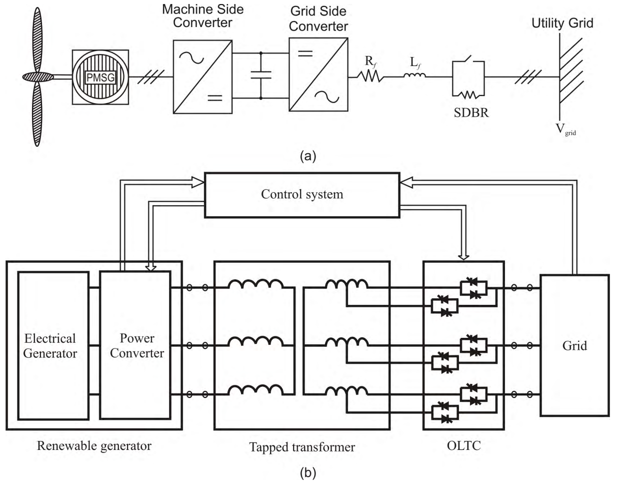

FIGURE 22. LVRT improvement of PMSG wind turbine using (a) series dynamic breaking resistor (b) active OLTC.

Active on-load tap changer (OLTC) also found to be effective in improvement of LVRT capability of wind turbine based PMSG. It consists of electronic components as illustrated in Fig. 22 (b). Transformer used for grid integration of PMSG is modified to have tape changer on grid side which helps to increase current boosting capacity. It also helps to provide speed required in process of tap changing. This additional feature increases voltage on generator side and also increases LVRT capability of wind turbine [153].

A method using pitch angle control, DC-link control and inertia of wind turbine for smoothing output power of WECS based on PMSG and improving LVRT capability during events of grid faults has been proposed in [154]. An LVRT strategy using cascaded current source converters (CSCs) on grid and generator sides for the offshore wind farm based on PMSG has been proposed in [155]. Short circuit operating ability of CSC is employed to develop an LVRT strategy. Table 17 provides a comparative study of various types of methods used for LVRT capability improvement.

VII. LVRT METHODS FOR SCIG WIND TURBINES

Fig. 7 (c) illustrates the system of the wind turbine which uses a fixed speed induction generator (FSIG). The basic configuration consists of a wind turbine (WT) including rotor, gearbox, SCIG, soft starter, mechanically switched capacitor and a transformer used for grid integration of FSIG. The rotor of SCIG driven by wind turbine and utility grid network directly connects with the stator winding. The wind turbine output mechanical power is converted into electrical power. Thereafter, it is transmitted to the grid through stator winding. Pitch angle controller is utilized to control generator output. SCIG consumes reactive power after a fault and voltage restoration is delayed. This process may lead to instability of rotor speed and voltage. During the faulty event, the generator accelerates due to the imbalance between mechanical and electrical powers. After fault clearance, the SCIG consumes reactive power and voltage restors to the nominal value. If the voltage does not rise quickly, the generator consumes more reactive power which may lead to voltage and rotor speed instability. LVRT enhancement methods are required for FSIG based wind power plants to overcome this problem [156]. Fig. 23 provides the classification of different LVRT methods used for the SCIG based wind power plants. Following subsections detail commonly used LVRT capability methods of SCIG based WECS.

A. SERIES CONNECTED DEVICES BASED LVRT METHODS

These devices have a series connection between the generator and the grid. This technology has a smaller current injection capacity compared to shunt connected technology. It has the capability of voltage regulation and limiting fault current which significantly increases transient and voltage stabilities in utility system [157]. Following subsections feature a brief discussion of series connected LVRT solutions for SCIG.

1) DYNAMIC VOLTAGE RESTORER BASED LVRT METHODS

The DVR is a power electronic device which is capable of injecting an appropriate voltage in the same phase as that of network voltage at PCC as illustrated in Fig. 24. A DVR must have the capacity to store sufficient energy which may be used to generate an appropriate voltage at generator terminals during voltage dips caused due to faulty event [158]. Fig. 25 displays a single-phase voltage phasor diagram for the operation of DVR during voltage dips. Voltage dip decreases voltage magnitude and causes a change in phase angle (δ). Change in phase angle is equal to the difference between pre-fault and during fault phase angle given by the following relation [159].

$$\delta = \arctan\left(\frac{X_F}{R_F}\right) - \arctan\left(\frac{X_s + X_F}{R_s + R_F}\right) \tag{13}$$

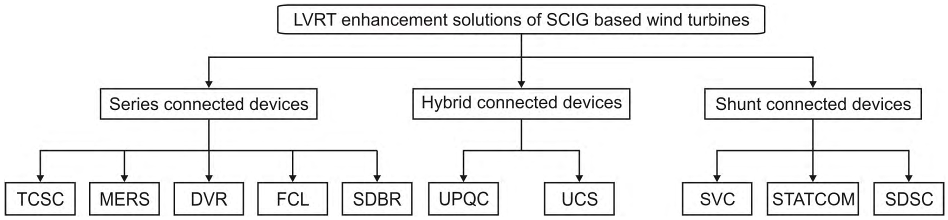

FIGURE 23. LVRT schemes for SCIG based wind power plants.

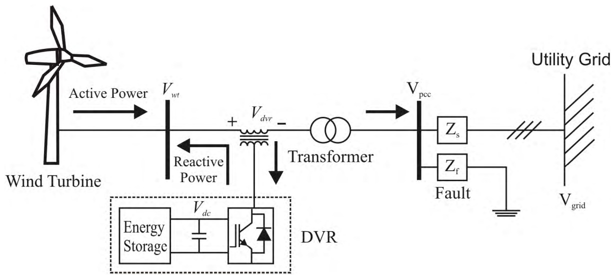

FIGURE 24. Operational principle of DVR and power flow during LVRT improvement.

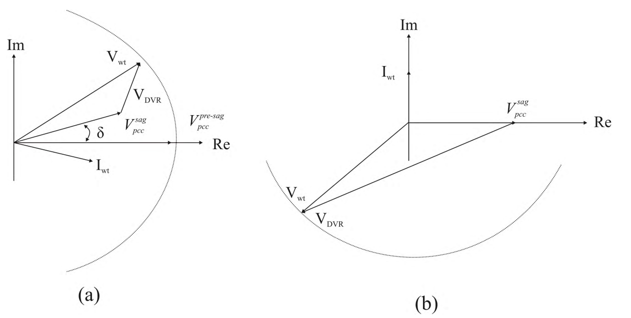

FIGURE 25. Vector diagram of single phase (a) DVR used for compensation of voltage dip (b) compensation of voltage dip after phasor rotation.

where $Z_F = R_F + jX_F$ and $Z_s = R_s + jX_s$ are respectively grid and fault impedances. A sudden change in phase-angle indicates the presence of a shift in zero crossings of instantaneous voltage. This strategy causes the internal flux of the generator to be out of phase with a voltage which results in large magnitude transients at the beginning and end of sag in voltage [160].

Reference [76] proposes a method for reactive power compensation of FSIG, enhancement of LVRT capability, mitigation of voltage sag and swell using DVR. In this method voltage injected by DVR is regulated to maintain a constant voltage on generator terminals and phase of generator terminal voltage lags the grid voltage by a constant angle by implementing phase angle control in DVR. Reference [161] proposes a method using DVR for improvement of LVRT capability of SCIG based WECS using the concept of critical clearing time. Reference [162] offers a comparative study between LVRT capability of DVR and superconductor fault current limiter (SFCL) for LVRT applications of SCIG wind farms.

2) THYRISTOR CONTROLLED SERIES CAPACITOR BASED LVRT METHODS

A module of thyristor controlled series capacitor (TCSC) comprises a fixed series capacitor and parallel connected thyristor controlled reactor (TCR). A series combination of a reactor and a bidirectional thyristor valve is used to form TCR circuit. TCR is fired with phase angle α concerning capacitor voltage which may range between 90° to 180° [163]. Fig. 26 (a) details the TCSC module along with basic control circuitry used for LVRT capability enhancement in SCIG based wind farms. The TCSC elements are capacitor (C), bypass inductor (L) and thyristors T_1 and T_2 which are kept forward biased [164]. Control circuitry is used to generate gate drive pulses of suitable widths for thyristors at the time of fault initiation. Variable capacitive reactance is obtained by injecting an additional current into a capacitor with the help of firing thyristor at zero crossings. This variable reactance compensates the reactive power which has been absorbed by induction generator which in turn improves the LVRT capability of SCIG wind turbine [165]. Reference [166] reports a method based on TCSC for system transient stability improvement and LVRT improvement of SCIG based wind farm. Reference [167] proposes an efficient control scheme of TCSC for LVRT capability improvement of SCIG.

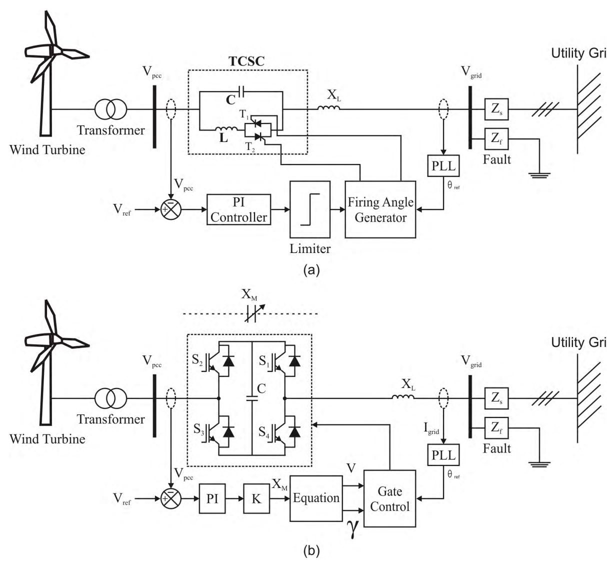

FIGURE 26. LVRT improvement of SCIG based wind farm using (a) TCSC (b) MERS.

3) MAGNETIC ENERGY RECOVERY SWITCH BASED LVRT METHODS

The magnetic energy recovery switch (MERS) is a variable reactance connected between wind plant and utility grid as shown in Fig. 26 (b). It consists of four reverse conducting switches and a capacitor. It compensates for reactive power and controls terminal voltage of the generator to enhance LVRT capability of SCIG based wind turbine. This method has the advantage of low losses compared to PWM based method [168]. The operational principle of the MERS details in [169]. A detailed study of the MERS as series FACTS compensator is provided in [170]. Reference [171] presents a detailed study for LVRT of SCIG based wind farms using MERS based series FACTS controller.

4) SERIES DYNAMIC BRAKING RESISTOR BASED LVRT METHODS

The series dynamic braking resistor (SDBR) has the main objective to balance active power between wind turbine mechanical and electrical sides through the faulty event. This technique eliminates the requirement of control of pitch angle and compensation of reactive power and achieved by inserting a resistor between generator terminals and grid using a switch. This action provides voltage support on PCC which helps to achieve stability of electrical torque, power stability, and LVRT improvement during faulty event [172]. Fig. 27 provides the various types of SDBR arrangement used for LVRT improvement of SCIG. The static bypass switches provide the sub-cycle response and variable control of power. Fig. 28, illustrates power flow along the wind farm system. Excessive dynamic power stored in the drive train system and heat dissipates in the resistor. Effects of SDBR on voltages of PCC is illustrated using a phasor diagram shown in Fig. 29 [173]. A method using a series dynamic resistor for improvement of LVRT capability and stability of wind power plants based on induction generator has reported in [174].

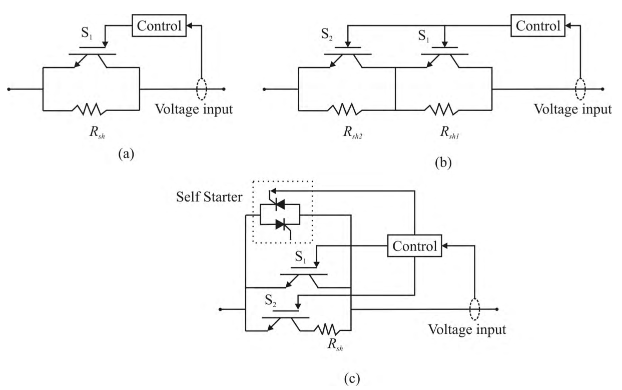

FIGURE 27. Series dynamic braking resistor for LVRT improvement of SCIG based wind farms (a) single stage arrangement (b) two stage arrangement (c) variable resistor arrangement with the use of soft starter.

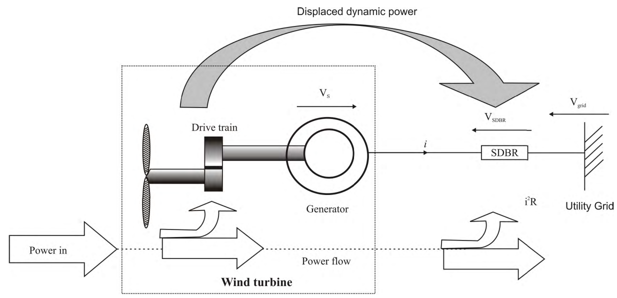

FIGURE 28. Series dynamic braking resistor for LVRT improvement of SCIG based wind farms with power flow during faulty conditions.

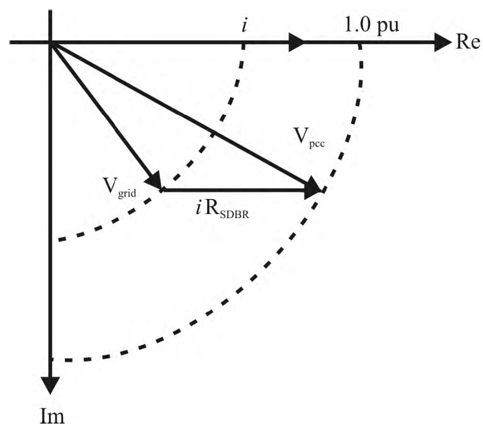

FIGURE 29. Single phase phasor diagram for LVRT improvement of SCIG based wind farms using SDBR.

5) FAULT CURRENT LIMITER BASED LVRT METHODS

Increased penetration of wind power into the utility grid network has raised its current fault level. To limit the current, various types of fault current limiters (FCL) have been being used. Commonly used FCLs for LVRT applications of fixed speed wind generation (FSWG) system include resonant circuit FCL, solid state type FCL, superconducting fault current limiter (SFCL) and bridge type fault current limiter (BFCL) [175]. A controllable resistive type fault current limiter (CR-FCL) to enhance the LVRT capability of FSWT reported in [176] is illustrated in Fig. 30 (a). The isolation transformer places in the series with a power system network. Three-phase diode rectifier is used to introduce DC side resistance (R) into the AC side of the system. Self turns off switch helps to limit fault current by putting resistance R in the circuit. Reactor (L_d) is used to protect the switch against large variations of fault current. In normal operation, resistance (R) is bypassed by the switch and introduced in the circuit during the faulty condition. Following is the relation between DC resistance (R) and AC resistance (R_{ac}).

$$R = \left(\frac{18a^2}{\pi^2}\right) R_{ac} \tag{14}$$

where a is isolation transformation ratio. Reference [177] reports an optimum resistive type FCL (OR-FCL) for reaching to maximum LVRT capability of FSWT during faulty events. A dedicated control circuit was used to introduce the optimized value for resistance in the circuit depending on the type and location of faults. Reference [178]

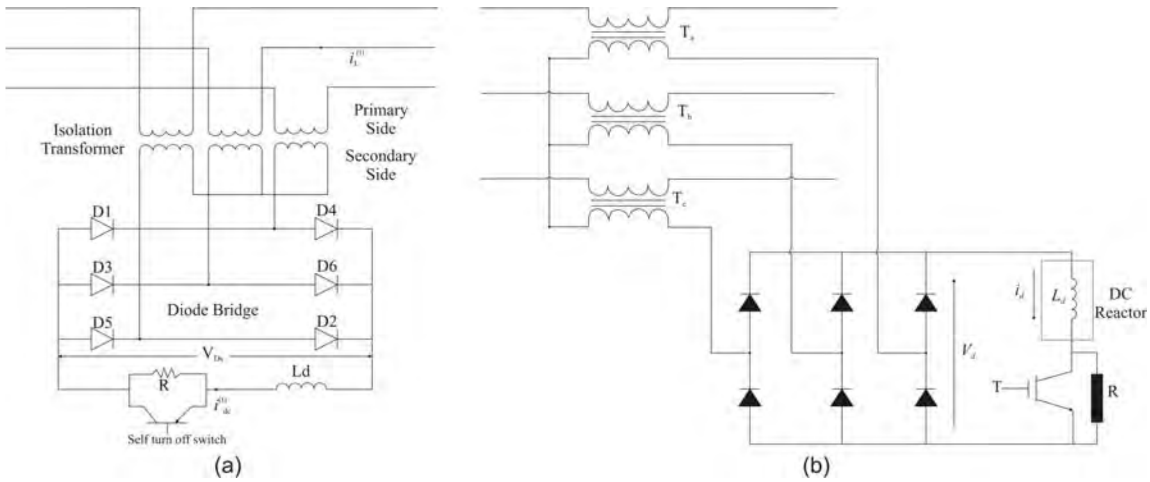

FIGURE 30. LVRT applications of FSWT system (a) power circuit topology of CR-FCL (b) bridge type FCL with discharging resistor.

published a transformer type fault current limiter (TFCL) using a DC reactor for LVRT improvement of FSWT power plants.

A bride type fault current limiter (BFCL) requires a coupling transformer with secondary winding having Y-connection, a DC reactor (L_d), a discharging resistor and a semiconductor switch (T) as shown in Fig. 30 (b). In the normal mode of operation, the resistor bypasses by closing the switch; DC reactor current is constant sand secondary of the transformer short-circuited. Therefore, the primary side of the transformer has very low impedance. During the faulty event, by controlling switching on and off periods of the switch, DC reactor current level is controlled. Hence, the terminal voltage is adjusted which improves the LVRT capability of FSWG wind turbines [179]. Reference [180] presents a BFCL with discharging resistor to enhance LVRT capability of FSWT. A revised arrangement of bridge type FCL for improving LVRT capability of fixed speed wind generator is reported in [181]. This approach also helps to follow the harmonic grid code.

The SFCL helps to restrict prospective fault current by suddenly increasing resistance value. It automatically detects excessive current and recovers from non-superconducting state to the superconducting state. Hence, any control action is not required. The SFCL effectively suppress fault current and control the wind terminal voltage and achieve LVRT action. Fig. 31, illustrates the resistive type SFCL and associated current and voltage profiles [182]. A superconducting wire of large length (R_{SFCL}) is in parallel connection with a shunt resistance (R_{shunt}). This arrangement controls current and hence voltage on wind generator terminals.

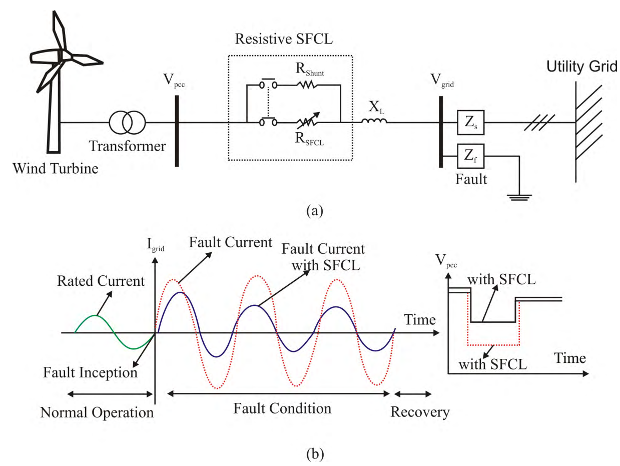

FIGURE 31. Resistive type SFCL with fault current and voltage profile on wind turbine terminals (a) circuit configuration (b) waveform.

B. SHUNT CONNECTED DEVICES BASED LVRT METHODS

These devices are connected in shunt connection at PCC to provide fast and smooth transient as well as steady state control of voltage at PCC. These devices inject reactive power at PCC and help to improve LVRT capability. Following subsections brief the overview of commonly used shunt devices for LVRT applications of FSWT.

1) STATIC SYNCHRONOUS COMPENSATOR BASED LVRT METHODS

The STATCOM used to enhance LVRT capability of FSWG wind turbines is illustrated in Fig. 32 (a). It consists of VSC equipped with IGBTs controlled by PWM technique. It is integrated to the grid at PCC using a transformer. It injects reactive power in the utility grid network or absorbs same from the grid. It is capable of eliminating the effects of both transient and steady-state disturbances [183]. Reference [184] proposes a method to investigate the impact of LVRT on the stability of FSWG wind turbines using a STATCOM. For LVRT enhancement of wind turbines with the fixed speed in faulty events, the precise model, design, SCIG, STATCOM and control of STATCOM have presented in Reference [185]. Reference [186] proposes a simplified

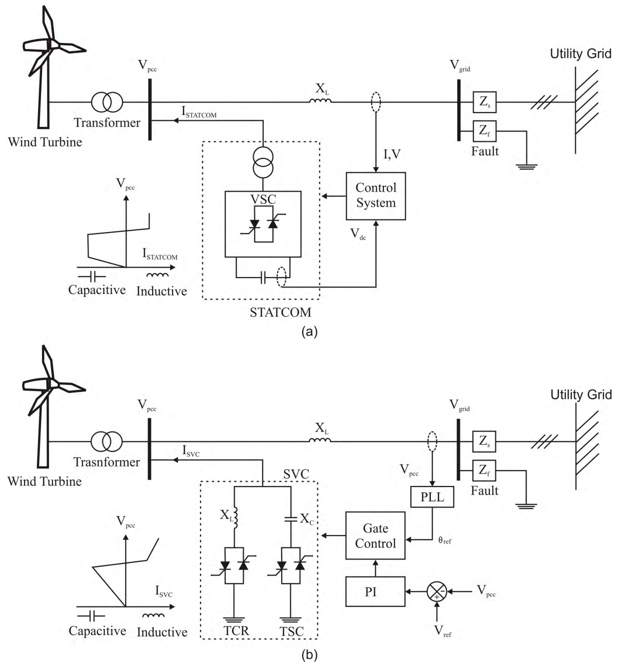

FIGURE 32. **LVRT improvement of SCIG based wind turbine (a) STATCOM (b) SVC.**

approach to find the rating of STATCOM for low voltage regulation on PCC and improvement of LVRT capability of fixed wind farms. In Reference [187], authors presents a combination of STATCOM and pitch angle control to improve the LVRT capability of the wind farm with FSWG. Reference [188] presents a control method to limit torque of grid-integrated SCIG using a STATCOM connected to machine terminals during grid faults. This method helps to achieve system transient stability and the capability of LVRT in the wind turbine.

2) STATIC VAR COMPENSATOR BASED LVRT METHODS

Static VAR compensator (SVC) consists of a combination of thyristor switched capacitor (TSC) and thyristor controlled reactor (TCR) which is connected to PCC as shown in Fig. 32 (b). This technique provides fast voltage support for improving the capability of LVRT in FSWG wind turbines. It also provides voltage support to loads, reactive power compensation and improves transient stability. Controllers used for LVRT applications of FSWG include proportional integral (PI), Fuzzy logic and sliding mode control [189]. Reference [190] presents a comparative study of STATCOM and SVC to improve dynamic stability and LVRT capability of wind farms. Ren *et al.* [191], proposes a novel means to improve the LVRT capability of FSWG wind turbines using a series reactor and an SVC.

3) SUPERCONDUCTING DYNAMIC SYNCHRONOUS CONDENSER BASED LVRT METHODS

The superconductor dynamic synchronous condenser (SDSC) is similar to the synchronous condenser where high-temperature superconductor (HTS) wires replace copper field winding. It has attractive features such as small footprints, high reliability, transportability, dynamic reactive compensation for both lagging and leading VARs. These machines also remain stable during close faults and provide twice the nominal rating during voltage sag events. These machines also found to be very much useful in providing LVRT capability to the FSWG wind farms [192], [193]. Application of SDSC in wind power integration to the utility network for improving LVRT capabilities of wind farms has reported in [194]. Reference [195] details a method for grid voltage support using SDSC.

C. HYBRID CONNECTED DEVICES BASED LVRT METHODS

The combined use of series and shunt devices to compare the reactive voltage and power at PCC is found to be an effective method for improvement of the capability of LVRT in large-sized wind farms. This combined use of series and shunt devices is known as hybrid solutions of LVRT. Unified compensation system (UCS) and unified power quality conditioner (UPQC) are two commonly used hybrid devices for LVRT applications of the FSWG wind turbines [196].

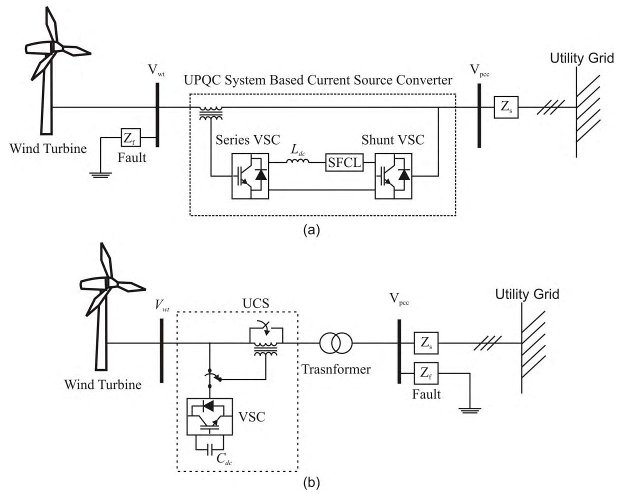

FIGURE 33. **LVRT improvement of SCIG based wind turbine using (a) UPQC (b) UCS.**

UPQC consists of an integration of series and shunt compensator and used to improve power quality disturbances such as voltage unbalance, voltage sag, harmonics and flicker. It also has the capability of regulating the dynamic active and reactive powers. Fig. 33 (a) [197] describes a structure of UPQC along with a resistive SFCL connected in series with DC-link inductor for LVRT improvement of SCIG based wind farms. A combinatorial method of UPQC and resistive SFCL for LVRT improvement of squirrel cage induction generator intends in [198]. Reference [199] publised methods based on the use of unified power flow controller (UPFC) and STATCOM for improvement of the capability of LVRT in WECS and to damp out rotor speed oscillations of the SCIG during faulty events.

TABLE 18. Comparison of LVRT methods of FSWG based WECS.

LVRT Method	Advantages	Disadvantages
TCSC	It has variable capacitive reactance which is useful to mitigate voltage unbalance and limit fault current.	It provides undesirable resonance and harmonic injection.
DVR	It provides controllable reactive power supply and fast voltage recovery.	It has a disadvantage of active power absorption and phase angle jump.
SDBR	It helps to mitigate mechanical active power and reduces pitch angle activation. It also provides high reliability to the system. Low maintenance is required	It is not able to control reactive power and damp out voltage fluctuations. It is not useful in low power factor uses.
MERS	It eliminates the use of reverse blocking switch. It has low switching losses and effective for large scale applications.	It provides less robust control and requires mechanical bypass switch.
BFCL	This technology is useful for high voltage drops. It minimizes rotor speed variations and has low conduction losses. Measurement of any parameters is not required.	It requires large scale coupling transformer. It provides large reactance in a wide range of applications. It provides undesirable saturation of DC reactance.
SFCL	It has the capability to detect fault current automatically. It also provides the fast fault current limiting action and automatic recovery.	It has high recovery time. It is not able to work at room temperature and also not able to control reactive power.
SVC	It provides reactive current injection, voltage stability in weak AC systems and continuous control of voltage.	Reactive control is dependent on voltage. It provides voltage oscillations of unstable nature because of a faster response.
STATCOM	It provides a reactive current which can be controlled, fast response to disturbances and reduction of negative sequence voltage.	It is not able to supply active power. It is required to cut off in a high voltage drop.
SDSC	It can perform with minimum losses and very high current for a long time.	It is less effective for applications of low voltage drops.
UPQC	It can provide both active as well as reactive power control. It also provides fast reactive power compensation. It has a long critical clearance time.	It absorbs active power and requires large capacity DC-link capacitor.
UCS	It can provide both series as well as shunt compensation using one converter.	It has high losses of conduction in the series bypass switch.

A topology based on combined series and shunt configuration known as a unified compensation system (UCS) for LVRT enhancement of fixed speed induction generator (FSIG) as depicted in Fig. 33 (b) is reported in [4]. In the normal mode of operation, the UCS operates just like a STATCOM to provide voltage support and compensation of reactive power. During faulty events, it switches from shunt to series operation and provides voltage compensation.

Table 18 demonstrates a comparative study of LVRT methods of FSWG based WECS.

VIII. FUTURE SCOPE OF RESEARCH

Nowadays, the attention of research is to increase the penetration level of RE sources into a network of utility grid which will help to meet our future energy demand using environment-friendly energy. The increased penetration level of wind energy into the utility grid network emphases that wind power plants remain connected during grid disturbances and faulty events to maintain transient and steady-state stability of the utility grid network. These improvements can be achieved by active control of the converters of these plants and providing LVRT enhancement methods. Therefore, it requires to investigate effective control methods for wind converters and LVRT improvement techniques which are effective even during significant scale disturbances in the grid. The contemporary trend is to make a hybrid grid by integrating various types of RE sources to the same grid. Therefore it requires to investigate LVRT methods which are useful even in the hybrid grid during disturbances. There is also a need to investigate coordinated control methods to improve the LVRT capability of wind power plants.

IX. CONCLUSION

This manuscript comprehensively review the literature concerning the improvement methods of the capability of LVRT of wind power plants has been carried out. Besides, it presents a detailed survey on the topic of LVRT techniques of grid-integrated wind energy systems which help the maintaining the wind generators connected to the utility grid in faulty events. Different types of international grid codes available for the integration of wind energy systems to the utility grid are analyzed critically, and their comparative study is presented. Commonly used wind generators and their LVRT methods have also been outlined. The methods used for LVRT improvement of DFIG-based wind turbines has been critically analyzed and their details in a comparative study are reviewed. LVRT improvement methods of PMSG based wind turbine have been critically surveyed and a comparative study is provided. A critical review of LVRT enhancement methods of SCIG based wind turbines and their comparative study is also presented. Finally, at the end of the manuscript, future scope for further research work to provide effective LVRT solutions to increase wind energy penetration level in the utility grid and hybrid energy systems is also presented.

According to the review developed in this manuscript, it is concluded that the wind energy conversion is widely in use environment-friendly renewable energy system which converts the wind kinetic energy into electrical energy. This generated electrical power is supplied to the utility grid. Commonly used wind generators with LVRT capability are DFIG, PMSG, and SCIG. Integration of wind power plants to the utility grid network has to meet out requirements of international grid codes defined by the utility operators. Most important grid code requirement in order that wind generators remain connected to the utility grid network during disturbances and faults is LVRT capability of the wind power plants. Comparative study of international grid codes, LVRT methods of DFIG, LVRT methods of PMSG and LVRT methods of SCIG presented in this paper will help to select an appropriate LVRT improvement method for the wind power plants. It will also help the researchers to carry out further research for the development of LVRT methods according to the requirements of the field. It is hoped that this critical review will be beneficial to utility operators, researchers, designers, manufacturers, and engineers in the field of grid integration of wind energy systems.

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REFERENCES

[1] Y. Ling and X. Cai, "Rotor current dynamics of doubly fed induction generators during grid voltage dip and rise," *Int. J. Electr. Power Energy Syst.*, vol. 44, no. 1, pp. 17–24, 2013.

[2] R. Khezri and H. Bevrani, "Voltage performance enhancement of DFIG-based wind farms integrated in large-scale power systems: Coordinated AVR and PSS," *Int. J. Electr. Power Energy Syst.*, vol. 73, pp. 400–410, Dec. 2015.

[3] Y. Lin, L. Tu, H. Liu, and W. Li, "Fault analysis of wind turbines in China," *Renew. Sustain. Energy Rev.*, vol. 55, pp. 482–490, Mar. 2016.

[4] P.-H. Huang, M. S. El Moursi, W. Xiao, and J. L. Kirtley, "Fault ride-through configuration and transient management scheme for self-excited induction generator-based wind turbine," *IEEE Trans. Sustain. Energy*, vol. 5, no. 1, pp. 148–159, Jan. 2014.

[5] A. Ajami and M. Armaghan, "Fixed speed wind farm operation improvement using current-source converter based UPQC," *Energy Convers. Manage.*, vol. 58, pp. 10–18, Jun. 2012.

[6] O. P. Mahela and A. G. Shaik, "Comprehensive overview of grid interfaced wind energy generation systems," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 260–281, May 2016.

[7] D. H. Nguyen and M. Negnevitsky, "A review of fault ride through strategies for different wind turbine systems," in *Proc. 20th Australas. Universities Power Eng. Conf.*, Dec. 2010, pp. 1–5.

[8] T. S. Abuaisha, "General study of the control principles and dynamic fault behaviour of variable-speed wind turbine and wind farm generic models," *Renew. Energy*, vol. 68, pp. 245–254, Aug. 2014.

[9] S. Yang, T. Zhou, L. Chang, Z. Xie, and X. Zhang, "Analytical method for DFIG transients during voltage dips," *IEEE Trans. Power Electron.*, vol. 32, no. 9, pp. 6863–6881, Sep. 2017.

[10] R. M. Kamel, "Employing two novel mechanical fault ride through controllers for keeping stability of fixed speed wind generation systems hosted by standalone micro-grid," *Appl. Energy*, vol. 116, pp. 398–408, Mar. 2014.

[11] K. M. Sunderland, G. Mills, and M. F. Conlon, "Estimating the wind resource in an urban area: A case study of micro-wind generation potential in Dublin, Ireland," *J. Wind Eng. Ind. Aerodyn.*, vol. 118, pp. 44–53, Jul. 2013.

[12] A. M. Eltamaly and H. M. Farh, "Maximum power extraction from wind energy system based on fuzzy logic control," *Electr. Power Syst. Res.*, vol. 97, pp. 144–150, Apr. 2013.

[13] M. Nasiri, J. Milimonfared, and S. H. Fathi, "A review of low-voltage ride-through enhancement methods for permanent magnet synchronous generator based wind turbines," *Renew. Sustain. Energy Rev.*, vol. 47, pp. 399–415, Jul. 2015.

[14] A. D. Hansen and G. Michalke, "Fault ride-through capability of DFIG wind turbines," *Renew. Energy*, vol. 32, no. 9, pp. 1594–1610, 2007.

[15] J. Yao, L. Guo, T. Zhou, D. Xu, and R. Liu, "Capacity configuration and coordinated operation of a hybrid wind farm with FSIG-based and PMSG-based wind farms during grid faults," *IEEE Trans. Energy Convers.*, vol. 32, no. 3, pp. 1188–1199, Sep. 2017.

[16] F. Hachicha and L. Krichen, "Rotor power control in doubly fed induction generator wind turbine under grid faults," *Energy*, vol. 44, no. 1, pp. 853–861, 2012.

[17] P. Dey, M. Datta, N. Fernando, and T. Senjyu, "Comparison of synchronous and stationary frame pi based flux weakening controls for DC-link overvoltage minimisation of WECS under grid fault," in *Proc. IEEE Region Conf. (TENCON)*, Nov. 2016, pp. 655–660.

[18] F. Jiang, C. Tu, Z. Shuai, F. Xiao, and Z. Lan, "Combinational voltage booster technique for fault ride-through capability enhancement of squirrel-cage induction generator," *Electr. Power Syst. Res.*, vol. 136, pp. 163–172, 2016.

[19] S. Xiao, H. Geng, H. Zhou, and G. Yang, "Analysis of the control limit for rotor-side converter of doubly fed induction generator-based wind energy conversion system under various voltage dips," *IET Renew. Power Gener.*, vol. 7, no. 1, pp. 71–81, Feb. 2013.

[20] X. Lin, K. Xiahou, Y. Liu, and Q. H. Wu, "Design and hardware-in-the-loop experiment of multiloop adaptive control for DFIG-WT," *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7049–7059, Sep. 2018.

[21] S. Divya and T. K. Krishna, "Combination of super capacitor-switch type fault current limiter for LVRT enhancement of DFIG wind turbines," in *Proc. Int. Conf. Control Commun. Comput. India (ICCC)*, Nov. 2015, pp. 343–348.

[22] A. Etxegarai, P. Eguia, E. Torres, G. Buigues, and A. Iturregi, "Current procedures and practices on grid code compliance verification of renewable power generation," *Renew. Sustain. Energy Rev.*, vol. 71, pp. 191–202, May 2017.

[23] I. A. Irazabal, E. Ciapessoni, D. Cirio, J. Glasdam, P. Lund, and A. Pitto, "Grid code compliant controllers for multi-terminal HVDC grids aimed to integrate wind power: Assessing their impact on the operational security of a real-world system," *Energy Procedia*, vol. 142, pp. 2165–2170, Dec. 2017.

[24] F. Díaz-González, M. Hau, A. Sumper, and O. Gomis-Bellmunt, "Participation of wind power plants in system frequency control: Review of grid code requirements and control methods," *Renew. Sustain. Energy Rev.*, vol. 34, pp. 551–564, Jun. 2014.

[25] A. B. Attya, J. L. Dominguez-Garcia, and O. Anaya-Lara, "A review on frequency support provision by wind power plants: Current and future challenges," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 2071–2087, Jan. 2018.

[26] A. Aziz, A. T. Oo, and A. Stojcevski, "Analysis of frequency sensitive wind plant penetration effect on load frequency control of hybrid power system," *Int. J. Elect. Power Energy Syst.*, vol. 99, pp. 603–617, Jul. 2018.

[27] A. K. Pathak, M. P. Sharma, and M. Bundele, "A critical review of voltage and reactive power management of wind farms," *Renew. Sustain. Energy Rev.*, vol. 51, pp. 460–471, Nov. 2015.

[28] G. Joos, "Wind turbine generator low voltage ride through requirements and solutions," in *Proc. IEEE Power Energy Soc. Gen. Meeting-Convers. Del. Elect. Energy 21st Century*, Jul. 2008, pp. 1–7.

[29] K. Loudiyi, A. Berrada, H. G. Svendsen, and K. Mentesidi, "Grid code status for wind farms interconnection in Northern Africa and Spain: Descriptions and recommendations for northern Africa," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 2584–2598, Jan. 2018.

[30] B. Singh and S. N. Singh, "Development of grid connection requirements for wind power generators in India," *Renew. Sustain. Energy Rev.*, vol. 15, no. 3, pp. 1669–1674, 2011.

[31] C.-G. Niu and G.-Q. Liu, "The requirements and technical analysis of low voltage ride through for the doubly-fed induction wind turbines," *Energy Procedia*, vol. 12, pp. 799–807, 2011.

[32] M. Mohseni and S. M. Islam, "Review of international grid codes for wind power integration: Diversity, technology and a case for global standard," *Renew. Sustain. Energy Rev.*, vol. 16, no. 6, pp. 3876–3890, 2012.

[33] E. M. G. Rodrigues, G. J. Osório, R. Godina, A. W. Bizuayehu, J. M. Lujano-Rojas, and J. P. S. Catalão, "Grid code reinforcements for deeper renewable generation in insular energy systems," *Renew. Sustain. Energy Rev.*, vol. 53, pp. 163–177, Jan. 2016.

[34] Z. Gao, X. Teng, X. Zhang, and R. Xu, "Solution of active power dispatch and control for interconnected power grids with large-scale wind power integration," *IFAC Proc. Volumes*, vol. 44, no. 1, pp. 14886–14891, 2011.

[35] Y.-L. Hu, Y.-K. Wu, C.-K. Chen, C.-H. Wang, W.-T. Chen, and L.-I. Cho, "A review of the low-voltage ride-through capability of wind power generators," *Energy Procedia*, vol. 141, pp. 378–382, Dec. 2017.

[36] A. M. Howlader and T. Senjyu, "A comprehensive review of low voltage ride through capability strategies for the wind energy conversion systems," *Renew. Sustain. Energy Rev.*, vol. 56, pp. 643–658, 2016.

[37] M. A. Saeed, H. M. Khan, A. Ashraf, and S. A. Qureshi, "Analyzing effectiveness of LVRT techniques for DFIG wind turbine system and implementation of hybrid combination with control schemes," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 2487–2501, Jan. 2018.

[38] C.-H. Park and G. Jang, "Voltage quality assessment considering low voltage ride-through requirement for wind turbines," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 16, pp. 4205–4212, Dec. 2016.

[39] L. Shaolin, Q. Shiyao, W. Ruiming, Y. Xuesong, and D. Linwang, "Study on voltage withstand characteristics and HVRT control strategy for DFIG wind turbines," in *Proc. Int. Conf. Power Syst. Technol. (POWERCON)*, Nov. 2018, pp. 1183–1189.

[40] A. M. S. Yunus, A. Abu-Siada, and M. A. S. Masoum, "Application of SMES unit to improve the high-voltage-ride-through capability of DFIG-grid connected during voltage swell," in *Proc. IEEE PES Innov. Smart Grid Technol.*, Nov. 2011, pp. 1–6.

[41] P. Song, Y. Zhang, K. Bai, J. Liu, H. Liu, and Y. Wu, "High voltage ride-through control method for DFIG-based wind turbines based on resonant controller," in *Proc. IEEE Int. Conf. Power Renew. Energy (ICPRE)*, Oct. 2016, pp. 67–71.

[42] S. Mali, S. James, and I. Tank, "Improving low voltage ride-through capabilities for grid connected wind turbine generator," *Energy Procedia*, vol. 54, pp. 530–540, Jan. 2014.

[43] S. I. Gkavanoudis and C. S. Demoulias, "A combined fault ride-through and power smoothing control method for full-converter wind turbines employing supercapacitor energy storage system," *Electr. Power Syst. Res.*, vol. 106, pp. 62–72, Jan. 2014.

[44] N. Espinoza, M. Bongiorno, and O. Carlson, "Novel LVRT testing method for wind turbines using flexible VSC technology," *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 1140–1149, Jul. 2015.

[45] M. Ndreko, M. Popov, and M. A. M. M. van der Meijden, "Study on FRT compliance of VSC-HVDC connected offshore wind plants during AC faults including requirements for the negative sequence current control," *Int. J. Elect. Power Energy Syst.*, vol. 85, pp. 97–116, Feb. 2017.

[46] R. Cárdenas, M. Díaz, F. Rojas, J. Clare, and P. Wheeler, "Resonant control system for low-voltage ride-through in wind energy conversion systems," *IET Power Electron.*, vol. 9, no. 6, pp. 1297–1305, May 2016.

[47] K. Tahir, C. Belfedal, T. Allaoui, and G. Champenois, "A new control strategy of WFSG-based wind turbine to enhance the LVRT capability," *Int. J. Electr. Power Energy Syst.*, vol. 79, pp. 172–187, Jul. 2016.

[48] K. Ma and F. Blaabjerg, "Modulation methods for neutral-point-clamped wind power converter achieving loss and thermal redistribution under low-voltage ride-through," *IEEE Trans. Ind. Electron.*, vol. 61, no. 2, pp. 835–845, Feb. 2014.

[49] E. M. Farahani, N. Hosseinzadeh, and M. Ektesabi, "Comparison of fault-ride-through capability of dual and single-rotor wind turbines," *Renew. Energy*, vol. 48, pp. 473–481, Dec. 2012.

[50] M. Benbouzid, B. Beltran, Y. Amirat, G. Yao, J. Han, and H. Mangel, "Second-order sliding mode control for DFIG-based wind turbines fault ride-through capability enhancement," *ISA Trans.*, vol. 53, no. 3, pp. 827–833, May 2014.

[51] J. Mohammadi, S. Afsharnia, and S. Vaez-Zadeh, "Efficient fault-ride-through control strategy of DFIG-based wind turbines during the grid faults," *Energy Convers. Manage.*, vol. 78, pp. 88–95, Feb. 2014.

[52] S. Yang, T. Zhou, L. Chang, R. Shao, X. Zhen, and X. Zhang, "An analytical method for the response of DFIG under voltage dips," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2015, pp. 963–970.

[53] S. Tohidi and B. Mohammadi-Ivatloo, "A comprehensive review of low voltage ride through of doubly fed induction wind generators," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 412–419, May 2016.

[54] J. Yang, J. E. Fletcher, and J. O'Reilly, "A series-dynamic-resistor-based converter protection scheme for doubly-fed induction generator during various fault conditions," *IEEE Trans. Energy Convers.*, vol. 25, no. 2, pp. 422–432, Jun. 2010.

[55] J. J. Justo and R. C. Bansal, "Parallel R-L configuration crowbar with series R-L circuit protection for LVRT strategy of DFIG under transient-state," *Electr. Power Syst. Res.*, vol. 154, pp. 299–310, Jan. 2018.

[56] Y. Mishra, S. Mishra, F. Li, and Z. Y. Dong, "Small signal stability analysis of a DFIG based wind power system with tuned damping controller under super/sub-synchronous mode of operation," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2009, pp. 1–8.

[57] M. Soliman, O. P. Malik, and D. T. Westwick, "Ensuring fault ride through for wind turbines with doubly fed induction generator: A model predictive control approach," *IFAC Proc. Volumes*, vol. 44, no. 1, pp. 1710–1715, 2011.

[58] Z. Zheng, G. Yang, and H. Geng, "Short circuit current analysis of DFIG-type WG with crowbar protection under grid faults," in *Proc. IEEE Int. Symp. Ind. Electron.*, May 2012, pp. 1072–1079.

[59] S. Swain and P. K. Ray, "Short circuit fault analysis in a grid connected DFIG based wind energy system with active crowbar protection circuit for ridethrough capability and power quality improvement," *Int. J. Elect. Power Energy Syst.*, vol. 84, pp. 64–75, Jan. 2017.

[60] S. Yang, T. Zhou, D. Sun, Z. Xie, and X. Zhang, "A SCR crowbar commutated with power converter for DFIG-based wind turbines," *Int. J. Elect. Power Energy Syst.*, vol. 81, pp. 87–103, Oct. 2016.

[61] M. Gholizadeh, S. Tohidi, A. Oraee, and H. Oraee, "Appropriate crowbar protection for improvement of brushless DFIG LVRT during asymmetrical voltage dips," *Int. J. Elect. Power Energy Syst.*, vol. 95, pp. 1–10, Feb. 2018.

[62] K. E. Okedu, S. M. Muyeen, R. Takahashi, and J. Tamura, "Wind farms fault ride through using DFIG with new protection scheme," *IEEE Trans. Sustain. Energy*, vol. 3, no. 2, pp. 242–254, Apr. 2012.

[63] M. Rahimi and M. Parniani, "Low voltage ride-through capability improvement of DFIG-based wind turbines under unbalanced voltage dips," *Int. J. Electr. Power Energy Syst.*, vol. 60, pp. 82–95, Sep. 2014.

[64] W. Gao, G. Wang, and J. Ning, "Development of low voltage ride-through control strategy for wind power generation using real time digital simulator," in *Proc. IEEE/PES Power Syst. Conf. Expo.*, Mar. 2009, pp. 1–6.

[65] M. Rahimi and M. Parniani, "Coordinated control approaches for low-voltage ride-through enhancement in wind turbines with doubly fed induction generators," *IEEE Trans. Energy Convers.*, vol. 25, no. 3, pp. 873–883, Sep. 2010.

[66] X. Yan, G. Venkataramanan, P. S. Flannery, Y. Wang, Q. Dong, and B. Zhang, "Voltage-sag tolerance of DFIG wind turbine with a series grid side passive-impedance network," *IEEE Trans. Energy Convers.*, vol. 25, no. 4, pp. 1048–1056, Dec. 2010.

[67] J. J. Justo, F. Mwasilu, and J.-W. Jung, "Doubly-fed induction generator based wind turbines: A comprehensive review of fault ride-through strategies," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 447–467, May 2015.

[68] J. Hu, B. Wang, W. Wang, H. Tang, Y. Chi, and Q. Hu, "Small signal dynamics of DFIG-based wind turbines during riding through symmetrical faults in weak AC grid," *IEEE Trans. Energy Convers.*, vol. 32, no. 2, pp. 720–730, Jun. 2017.

[69] G. Pannell, B. Zahawi, D. J. Atkinson, and P. Missailidis, "Evaluation of the performance of a DC-link brake chopper as a DFIG low-voltage fault-ride-through device," *IEEE Trans. Energy Convers.*, vol. 28, no. 3, pp. 535–542, Sep. 2013.

[70] A. R. A. Jerin, P. Kaliannan, and U. Subramaniam, "Improved fault ride through capability of DFIG based wind turbines using synchronous reference frame control based dynamic voltage restorer," *ISA Trans.*, vol. 70, pp. 465–474, Sep. 2017.

[71] J. G. Nielsen and F. Blaabjerg, "A detailed comparison of system topologies for dynamic voltage restorers," *IEEE Trans. Ind. Appl.*, vol. 41, no. 5, pp. 1272–1280, Sep. 2005.

[72] A. O. Ibrahim, T. H. Nguyen, D.-C. Lee, and S.-C. Kim, "A fault ride-through technique of DFIG wind turbine systems using dynamic voltage restorers," *IEEE Trans. Energy Convers.*, vol. 26, no. 3, pp. 871–882, Sep. 2011.

[73] S. I. Gkavanoudis and C. S. Demoulias, "Fault ride-through capability of a DFIG in isolated grids employing DVR and supercapacitor energy storage," *Int. J. Elect. Power Energy Syst.*, vol. 68, pp. 356–363, Jun. 2015.

[74] V. P. Suppioni, A. P. Grilo, and J. C. Teixeira, "Improving network voltage unbalance levels by controlling DFIG wind turbine using a dynamic voltage restorer," *Int. J. Electr. Power Energy Syst.*, vol. 96, pp. 185–193, Mar. 2018.

[75] R. Sitharthan, C. K. Sundarabalan, K. R. Devabalaji, and S. K. Nataraj, "Improved fault ride through capability of DFIG-wind turbines using customized dynamic voltage restorer," *Sustain. Cities Soc.*, vol. 39, pp. 114–125, May 2018.

[76] S. Priyavarthini, C. Nagamani, G. S. Ilango, and M. A. A. Rani, "An improved control for simultaneous sag/swell mitigation and reactive power support in a grid-connected wind farm with DVR," *Int. J. Elect. Power Energy Syst.*, vol. 101, pp. 38–49, Oct. 2018.

[77] S. Chondrogiannis and M. Barnes, "Specification of rotor side voltage source inverter of a doubly-fed induction generator for achieving ride-through capability," *IET Renew. Power Gener.*, vol. 2, no. 3, pp. 139–150, Sep. 2008.

[78] M. K. Döşoğlu, "A new approach for low voltage ride through capability in DFIG based wind farm," *Int. J. Elect. Power Energy Syst.*, vol. 83, pp. 251–258, Dec. 2016.

[79] Q. Huang, X. Zou, D. Zhu, and Y. Kang, "Scaled current tracking control for doubly fed induction generator to ride-through serious grid faults," *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 2150–2165, Mar. 2016.

[80] C. Wei, W. Qiao, and T. Kim, "Low-voltage ride-through performance of sensorless vector controlled doubly-fed induction generators," in *Proc. IEEE Int. Conf. Electro Inf. Technol. (EIT)*, May 2017, pp. 530–534.

[81] S. A. A. Shahriari, M. Mohammadi, and M. Raoofat, "A new method based on state-estimation technique to enhance low-voltage ride-through capability of doubly-fed induction generator wind turbines," *Int. J. Elect. Power Energy Syst.*, vol. 95, pp. 118–127, Feb. 2018.

[82] M. A. Bidgoli, H. A. Mohammadpour, and S. M. T. Bathaee, "Advanced vector control design for DFIM-based hydropower storage for fault ride-through enhancement," *IEEE Trans. Energy Convers.*, vol. 30, no. 4, pp. 1449–1459, Dec. 2015.

[83] C.-C. Chu, Y.-Z. Lin, J.-H. Liu, and S.-K. Ho, "Fault ride-through enhancements of wind turbine with doubly-fed induction generator using the robust variable structure system control," in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2010, pp. 2515–2520.

[84] D. V. N. Ananth and G. V. N. Kumar, "Fault ride-through enhancement using an enhanced field oriented control technique for converters of grid connected DFIG and STATCOM for different types of faults," *ISA Trans.*, vol. 62, pp. 2–18, May 2016.

[85] G. Rashid and M. H. Ali, "Fault ride through capability improvement of DFIG based wind farm by fuzzy logic controlled parallel resonance fault current limiter," *Electr. Power Syst. Res.*, vol. 146, pp. 1–8, May 2017.

[86] M. E. Hossain, "A non-linear controller based new bridge type fault current limiter for transient stability enhancement of DFIG based wind farm," *Electr. Power Syst. Res.*, vol. 152, pp. 466–484, Nov. 2017.

[87] M. J. Morshed and A. Fekih, "A new fault ride-through control for DFIG-based wind energy systems," *Electr. Power Syst. Res.*, vol. 146, pp. 258–269, May 2017.

[88] N. Amuthan, P. Subburaj, and P. M. Mary, "Direct model reference adaptive internal model controller for better voltage sag ride through in doubly fed induction generator wind farms," *Int. J. Elect. Power Energy Syst.*, vol. 47, pp. 255–263, May 2013.

[89] D. Zhu, X. Zou, S. Zhou, W. Dong, Y. Kang, and J. Hu, "Feedforward current references control for DFIG-based wind turbine to improve transient control performance during grid faults," *IEEE Trans. Energy Convers.*, vol. 32, no. 2, pp. 670–681, Jun. 2018.

[90] M. Abdelrahem and R. Kennel, "Direct-model predictive control for fault ride-through capability enhancement of DFIG," in *Proc. Eur., Int. Exhib. Conf. Power Electron., Intell. Motion, Renew. Energy Energy Manage. (PCIM)*, May 2017, pp. 1–8.

[91] N. Amuthan, P. Subburaj, and P. M. Mary, "Voltage sag ride through using improved adaptive internal model controller for doubly fed induction generator wind farms," *Comput. Elect. Eng.*, vol. 39, no. 2, pp. 214–224, 2013.

[92] M. Mohseni, M. A. S. Masoum, and S. M. Islam, "Low and high voltage ride-through of DFIG wind turbines using hybrid current controlled converters," *Electr. Power Syst. Res.*, vol. 81, no. 7, pp. 1456–1465, 2011.

[93] J. J. Justo, F. Mwasilu, and J.-W. Jung, "Enhanced crowbarless FRT strategy for DFIG based wind turbines under three-phase voltage dip," *Electr. Power Syst. Res.*, vol. 142, pp. 215–226, Jan. 2017.

[94] T. D. Vrionis, X. I. Koutiva, and N. A. Vovos, "A genetic algorithm-based low voltage ride-through control strategy for grid connected doubly fed induction wind generators," *IEEE Trans. Power Syst.*, vol. 29, no. 3, pp. 1325–1334, May 2014.

[95] M. Mohseni, S. Islam, and M. A. S. Masoum, "Fault ride-through capability enhancement of doubly-fed induction wind generators," *IET Renew. Power Gener.*, vol. 5, no. 5, pp. 368–376, Sep. 2011.

[96] S. Xiao, G. Yang, H. Zhou, and H. Geng, "An LVRT control strategy based on flux linkage tracking for DFIG-based WECS," *IEEE Trans. Ind. Electron.*, vol. 60, no. 7, pp. 2820–2832, Jul. 2013.

[97] S. Q. Bu, W. Du, H. F. Wang, and S. Gao, "Power angle control of grid-connected doubly fed induction generator wind turbines for fault ride-through," *IET Renew. Power Gener.*, vol. 7, no. 1, pp. 18–27, Feb. 2013.

[98] D. Zhu, X. Zou, L. Deng, Q. Huang, S. Zhou, and Y. Kang, "Inductance-emulating control for DFIG-based wind turbine to ride-through grid faults," *IEEE Trans. Power Electron.*, vol. 32, no. 11, pp. 8514–8525, Nov. 2017.

[99] J. Mohammadi, S. Afsharnia, S. Vaez-Zadeh, and S. Farhangi, "Improved fault ride through strategy for doubly fed induction generator based wind turbines under both symmetrical and asymmetrical grid faults," *IET Renew. Power Gener.*, vol. 10, no. 8, pp. 1114–1122, Sep. 2016.

[100] 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, Jun. 2015.

[101] X. Zou, D. Zhu, J. Hu, S. Zhou, and Y. Kang, "Mechanism analysis of the required rotor current and voltage for DFIG-based wts to ride-through severe symmetrical grid faults," *IEEE Trans. Power Electron.*, vol. 33, no. 9, pp. 7300–7304, Sep. 2018.

[102] R. Zhu, Z. Chen, Y. Tang, F. Deng, and X. Wu, "Dual-loop control strategy for DFIG-based wind turbines under grid voltage disturbances," *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 2239–2253, Mar. 2016.

[103] L. Zhou, J. Liu, and S. Zhou, "Improved demagnetization control of a doubly-fed induction generator under balanced grid fault," *IEEE Trans. Power Electron.*, vol. 30, no. 12, pp. 6695–6705, Dec. 2015.

[104] Y.-W. Shen, D.-P. Ke, W. Qiao, Y.-Z. Sun, D. S. Kirschen, and C. Wei, "Transient reconfiguration and coordinated control for power converters to enhance the LVRT of a DFIG wind turbine with an energy storage device," *IEEE Trans. Energy Convers.*, vol. 30, no. 4, pp. 1679–1690, Dec. 2015.

[105] M. K. Hossain and M. H. Ali, "Transient stability augmentation of PV/DFIG/SG-based hybrid power system by parallel-resonance bridge fault current limiter," *Electr. Power Syst. Res.*, vol. 130, pp. 89–102, Jan. 2016.

[106] W. Li, P. Chao, X. Liang, Y. Sun, J. Qi, and X. Chang, "Modeling of complete fault ride-through processes for DFIG-based wind turbines," *Renew. Energy*, vol. 118, pp. 1001–1014, Apr. 2018.

[107] S. B. Naderi, M. Negnevitsky, A. Jalilian, M. T. Hagh, and K. M. Muttaqi, "Low voltage ride-through enhancement of DFIG-based wind turbine using DC link switchable resistive type fault current limiter," *Int. J. Elect. Power Energy Syst.*, vol. 86, pp. 104–119, Mar. 2017.

[108] A. Damdoum, I. Slama-Belkhodja, M. Pietrzak-David, and M. Debbou, "Low voltage ride-through strategies for doubly fed induction machine pumped storage system under grid faults," *Renew. Energy*, vol. 95, pp. 248–262, Sep. 2016.

[109] H. Mohammadpour, S. G. Zadeh, and S. Tohidi, "Symmetrical and asymmetrical low-voltage ride through of doubly-fed induction generator wind turbines using gate controlled series capacitor," *IET Renew. Power Gener.*, vol. 9, no. 7, pp. 840–846, Sep. 2015.

[110] M. E. Hossain, "Improvement of transient stability of DFIG based wind generator by using of resistive solid state fault current limiter," *Ain Shams Eng. J.*, vol. 9, no. 4, pp. 2557–2570, 2017.

[111] S. Tohidi, P. Tavner, R. McMahon, H. Oraee, M. R. Zolghadri, S. Shao, and E. Abdi, "Low voltage ride-through of DFIG and brushless DFIG: Similarities and differences," *Electr. Power Syst. Res.*, vol. 110, pp. 64–72, May 2014.

[112] K. Vinothkumar and M. P. Selvan, "Novel scheme for enhancement of fault ride-through capability of doubly fed induction generator based wind farms," *Energy Convers. Manage.*, vol. 52, no. 7, pp. 2651–2658, 2011.

[113] H. Mahvash and S. A. Taher, "A look-up table based approach for fault ride-through capability enhancement of a grid connected DFIG wind turbine," *Sustain. Energy, Grids Netw.*, vol. 10, pp. 128–140, Jun. 2017.

[114] A. Adouni, D. Chariag, D. Diallo, M. B. Hamed, and L. Sbita, "FDI based on artificial neural network for low-voltage-ride-through in DFIG-based wind turbine," *ISA Trans.*, vol. 64, pp. 353–364, Sep. 2016.
[115] Z. C. Zou, X. Y. Xiao, R. Ou, C. S. Li, and Y. Zhang, "Low-voltage ride-through capability enhancement of DFIG-based wind turbine with a resistive-type SFCL connected in series with rotor winding," in *Proc. IEEE Int. Conf. Appl. Supercond. Electromagn. Devices (ASEMD)*, Nov. 2015, pp. 42–43.
[116] M. Abdelrahem, M. H. Mobarak, and R. Kennel, "Realization of low-voltage ride through requirements for PMSGs in wind turbines systems using generator-rotor inertia," in *Proc. 9th Int. Conf. Elect. Comput. Eng. (ICECE)*, Dec. 2016, pp. 54–57.
[117] D. J. Bang, H. Polinder, G. Shrestha, and J. A. Ferreira, "Promising direct-drive generator system for large wind turbines," *Eur. Power Electron. Drives*, vol. 18, no. 3, pp. 7–13, Mar. 2008.
[118] Y. Errami, M. Ouassaid, and M. Maaroufi, "A performance comparison of a nonlinear and a linear control for grid connected PMSG wind energy conversion system," *Int. J. Electr. Power Energy Syst.*, vol. 68, pp. 180–194, Jun. 2015.
[119] T. H. Nguyen and D.-C. Lee, "Ride-through technique for PMSG wind turbines using energy storage systems," *J. Power Electron.*, vol. 10, no. 6, pp. 733–738, 2010.
[120] F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, and R. Villafáfila-Robles, "A review of energy storage technologies for wind power applications," *Renew. Sustain. Energy Rev.*, vol. 16, no. 4, pp. 2154–2171, May 2012.
[121] I. Hadjipaschalis, A. Poullikkas, and V. Efthimiou, "Overview of current and future energy storage technologies for electric power applications," *Renew. Sustain. Energy Rev.*, vol. 13, nos. 6–7, pp. 1513–1522, 2009.
[122] F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, and F. D. Bianchi, "Energy management of flywheel-based energy storage device for wind power smoothing," *Appl. Energy*, vol. 110, pp. 207–219, Oct. 2013.
[123] J. Shi, Y. J. Tang, L. Ren, J. D. Li, and S. J. Chen, "Application of SMES in wind farm to improve voltage stability," *Phys. C, Supercond.*, vol. 468, nos. 15–20, pp. 2100–2103, 2008.
[124] T. Hamajima, H. Amata, T. Iwasaki, N. Atomura, M. Tsuda, D. Miyagi, T. Shintomi, Y. Makida, T. Takao, K. Munakata, and M. Kajiwara, "Application of SMES and fuel cell system combined with liquid hydrogen vehicle station to renewable energy control," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Jun. 2012, Art. no. 5701704.
[125] G. H. Kim, A. R. Kim, S. Kim, M. Park, I. K. Yu, K. C. Seong, and Y. J. Won, "A novel HTS SMES application in combination with a permanent magnet synchronous generator type wind power generation system," *Phys. C, Supercond. Appl.*, vol. 471, nos. 21–22, pp. 1413–1418, 2011.
[126] P. P. Barker, "Ultracapacitors for use in power quality and distributed resource applications," in *Proc. IEEE Power Eng. Soc. Summer Meeting*, vol. 1, Jul. 2002, pp. 316–320.
[127] Y. Y. Chia, L. H. Lee, N. Shafiabady, and D. Isa, "A load predictive energy management system for supercapacitor-battery hybrid energy storage system in solar application using the support vector machine," *Appl. Energy*, vol. 137, pp. 588–602, Jan. 2015.
[128] C. Abbey and G. Joos, "Supercapacitor energy storage for wind energy applications," *IEEE Trans. Ind. Appl.*, vol. 43, no. 3, pp. 769–776, May 2007.
[129] T. H. Nguyen and D.-C. Lee, "Advanced fault ride-through technique for PMSG wind turbine systems using line-side converter as STATCOM," *IEEE Trans. Ind. Electron.*, vol. 60, no. 7, pp. 2842–2850, Jul. 2013.
[130] O. P. Mahela and A. G. Shaik, "Topological aspects of power quality improvement techniques: A comprehensive overview," *Renew. Sustain. Energy Rev.*, vol. 58, pp. 1129–1142, May 2016.
[131] Z. Chen, J. M. Guerrero, and F. Blaabjerg, "A review of the state of the art of power electronics for wind turbines," *IEEE Trans. Power Electron.*, vol. 24, no. 8, pp. 1859–1875, Aug. 2009.
[132] M. Molinas, J. A. Suul, and T. Undeland, "Low voltage ride through of wind farms with cage generators: STATCOM Versus SVC," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1104–1117, May 2008.
[133] M. Farhadi-Kangarlu, E. Babaei, and F. Blaabjerg, "A comprehensive review of dynamic voltage restorers," *Int. J. Electr. Power Energy Syst.*, vol. 92, pp. 136–155, Nov. 2017.
[134] K.-M. Jin, Q. N. Thinh, and E.-H. Kim, "DVR control of DFIG for compensating fault ride-through based on stationary and synchronous reference frame," in *Proc. 7th Int. Power Electron. Motion Control Conf.*, vol. 2, Jun. 2012, pp. 3004–3009.
[135] S. Raphael and A. Massoud, "Unified power flow controller for low voltage ride through capability of wind-based renewable energy grid-connected systems," in *Proc. 8th Int. Multi-Conf. Syst., Signals Devices*, Mar. 2011, pp. 1–6.
[136] N. Heng, L. Jiao, Z. Peng, and H. Yikang, "Improved control strategy of an active crowbar for directly-driven PM wind generation system under gridv oltage dips," in *Proc. Int. Conf. Elect. Mach. Syst.*, Oct. 2008, pp. 2294–2298.
[137] Z. Qiu, K. Zhou, and Y. Li, "Modeling and control of diode rectifier fed PMSG based wind turbine," in *Proc. 4th Int. Conf. Electr. Utility Deregulation Restruct. Power Technol. (DRPT)*, Jul. 2011, pp. 1384–1388.
[138] A. D. Hansen and G. Michalke, "Multi-pole permanent magnet synchronous generator wind turbines' grid support capability in uninterrupted operation during grid faults," *IET Renew. Power Gener.*, vol. 3, no. 3, pp. 333–348, Sep. 2009.
[139] A. K. Thet and H. Saitoh, "Pitch control for improving the low-voltage ride-through of wind farm," in *Proc. Transmiss. Distrib. Conf. Expo., Asia Pacific*, Oct. 2009, pp. 1–4.
[140] M. R. Hazari, A. Umemura, R. Takahashi, J. Tamura, and M. A. Mannan, "A new fuzzy logic based control strategy for variable speed wind generator to enhance the transient stability of fixed speed wind generator," in *Proc. IEEE Manchester PowerTech*, Jun. 2017, pp. 1–6.
[141] M. Khalid and A. V. Savkin, "Model predictive control for wind power generation smoothing with controlled battery storage," in *Proc. 48th IEEE Conf. Decis. Control (CDC)*, Dec. 2009, pp. 7849–7853.
[142] Z. Liu, C. Liu, and G. Li, "Power coordinated control of wind turbines with permanent magnet synchronous generator for low voltage ride through," in *Proc. IEEE PES Gen. Meeting Conf. Expo.*, Jul. 2014, pp. 1–5.
[143] S. Li, T. A. Haskew, R. P. Swatloski, and W. Gathings, "Optimal and direct-current vector control of direct-driven PMSG wind turbines," *IEEE Trans. Power Electron.*, vol. 27, no. 5, pp. 2325–2337, May 2012.
[144] M. Wang, Y. Hu, W. Zhao, Y. Wang, and G. Chen, "Application of modular multilevel converter in medium voltage high power permanent magnet synchronous generator wind energy conversion systems," *IET Renew. Power Gener.*, vol. 10, no. 6, pp. 824–833, Jul. 2016.
[145] V. Yaramasu, B. Wu, S. Alepuz, and S. Kouro, "Predictive control for low-voltage ride-through enhancement of three-level-boost and NPC-converter-based PMSG wind turbine," *IEEE Trans. Ind. Electron.*, vol. 61, no. 12, pp. 6832–6843, Dec. 2014.
[146] L. S. Barros and C. M. V. Barros, "An internal model control for enhanced grid-connection of direct-driven PMSG-based wind generators," *Electr. Power Syst. Res.*, vol. 151, pp. 440–450, Oct. 2017.
[147] O. Anaya-Lara, N. Jenkins, J. Ekanayake, P. Cartwright, and F. Hughes, *Wind Energy Generation: Modelling and Control*. 2009.
[148] P. Dey, M. Datta, N. Fernando, and T. Senjyu, "A method to reduce DC-link overvoltage of PMSG based WECS during LVRT," in *Proc. IEEE Region Conf. (TENCON)*, Nov. 2016, pp. 1894–1899.
[149] D. Jeong, C. Kim, Y. Gui, and C. C. Chung, "Sliding mode control for LVRT of a PMSG wind turbine using stored energy in rotor inertia," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Jul. 2016, pp. 1–5.
[150] P. Xing, L. Fu, G. Wang, Y. Wang, and Y. Zhang, "A compositive control method of low-voltage ride through for PMSG-based wind turbine generator system," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 1, pp. 117–125, Jan. 2018.
[151] N. H. Saad, A. A. El-Sattar, and M. E. Marei, "Improved bacterial foraging optimization for grid connected wind energy conversion system based PMSG with matrix converter," *Ain Shams Eng. J.*, vol. 9, no. 4, pp. 2183–2193, 2018.
[152] T. Ji, X. He, X. Li, K. Liu, and M. Zhang, "Performance analysis and research on LVRT of PMSG wind power systems with SDBR," in *Proc. 33rd Chin. Control Conf.*, Jul. 2014, pp. 6953–6958.
[153] D. Ramirez, S. Martinez, C. Carrero, and C. A. Platero, "Improvements in the grid connection of renewable generators with full power converters," *Renew. Energy*, vol. 43, pp. 90–100, Jul. 2012.
[154] A. Pratap, N. Urasaki, and T. Senjyu, "Smoothing of output power of PMSG-based WECS and enhancing FRT during grid faults," in *Proc. IEEE 10th Int. Conf. Power Electron. Drive Syst. (PEDS)*, Apr. 2013, pp. 457–462.
[155] M. Popat, B. Wu, and N. R. Zargari, "Fault ride-through capability of cascaded current-source converter-based offshore wind farm," *IEEE Trans. Sustain. Energy*, vol. 4, no. 2, pp. 314–323, Apr. 2013.

[156] M. J. Hossain, H. R. Pota, and R. A. Ramos, "Robust STATCOM control for the stabilisation of fixed-speed wind turbines during low voltages," *Renew. Energy*, vol. 36, no. 11, pp. 2897–2905, 2011.

[157] L. Piyasinghe, Z. Miao, J. Khazaei, and L. Fan, "Impedance model-based SSR analysis for TCSC compensated type-3 wind energy delivery systems," *IEEE Trans. Sustain. Energy*, vol. 6, no. 1, pp. 179–187, Jan. 2015.

[158] P. Sebastian and U. Nair, "Improved low voltage ride through capability of a fixed speed wind generator using dynamic voltage restorer," *Procedia Technol.*, vol. 25, pp. 767–774, Jan. 2016.

[159] G. Sivasankar and V. S. Kumar, "Improving low voltage ride through capability of wind generators using dynamic voltage restorer," *J. Electr. Eng.*, vol. 65, no. 4, pp. 235–241, Aug. 2014.

[160] H. Gaztanaga, I. Etxeberria-Otadui, S. Bacha, and D. Roye, "Fixed-speed wind farm operation improvement by using DVR devices," in *Proc. IEEE Int. Symp. Ind. Electron.*, Jun. 2007, pp. 2679–2684.

[161] N. Amutha and B. K. Kumar, "Improving fault ride-through capability of wind generation system using DVR," *Int. J. Electr. Power Energy Syst.*, vol. 46, pp. 326–333, Mar. 2013.

[162] A. A. Hussein and M. H. Ali, "Comparison between DVR and SFCL for fault ride through capability improvement of fixed-speed wind generator," in *Proc. IEEE PES T D Conf. Expo.*, Apr. 2014, pp. 1–5.

[163] A. D. D. Rosso, C. A. Canizares, and V. M. Dona, "A study of TCSC controller design for power system stability improvement," *IEEE Trans. Power Syst.*, vol. 18, no. 4, pp. 1487–1496, Nov. 2003.

[164] M. Eslami, H. Shareef, and A. Mohamed, "Coordinated design of PSS and TCSC controller for power system stability improvement," in *Proc. Conf. IPEC*, Oct. 2010, pp. 433–438.

[165] N. N. Joshi and N. Mohan, "Application of TCSC in wind farm application," in *Proc. Int. Symp. Power Electron., Elect. Drives, Automat. Motion (SPEEDAM)*, May 2006, pp. 1196–1200.

[166] H. Zhou, H. Wei, X. Qiu, J. Xu, X. Wei, and S. Wang, "Improvement of transient voltage stability of the wind farm using SVC and TCSC," in *Proc. Asia–Pacific Power Energy Eng. Conf.*, Mar. 2011, pp. 1–4.

[167] H. A. Mohammadpour, A. Ghaderi, H. Mohammadpour, and M. H. Ali, "Low voltage ride-through enhancement of fixed-speed wind farms using series FACTS controllers," *Sustain. Energy Technol. Assessments*, vol. 9, pp. 12–21, Mar. 2015.

[168] J. A. Wiik, F. D. Wijaya, and R. Shimada, "Characteristics of the magnetic energy recovery switch (MERS) as a series FACTS controller," *IEEE Trans. Power Del.*, vol. 24, no. 2, pp. 828–836, Apr. 2009.

[169] J. A. Wiik, F. D. Widjaya, T. Isobe, T. Kitahara, and R. Shimada, "Series connected power flow control using magnetic energy recovery switch (MERS)," in *Proc. Power Convers. Conf.-Nagoya*, Apr. 2007, pp. 983–990.

[170] P. Bakkiavathi and C. C. A. Rajan, "Performance of magnetic energy recovery switch as a series FACTS controller," in *Proc. Int. Conf. Power, Energy Control (ICPEC)*, Feb. 2013, pp. 92–97.

[171] J. A. Wiik, O. J. Fonstelien, and R. Shimada, "A MERS type series facts controller for low voltage ride through of induction generators in wind farms," in *Proc. 13th Eur. Conf. Power Electron. Appl.*, Sep. 2009, pp. 1–10.

[172] M. A. H. Soliman, H. Soliman, and P. K. Soori, "Analysis of the dynamic behavior and LVRT capability of a DFIG using SDBR during grid disturbances," in *Proc. 7th IEEE GCC Conf. Exhibit. (GCC)*, Nov. 2013, pp. 436–439.

[173] A. Causebrook, D. J. Atkinson, and A. G. Jack, "Fault ride-through of large wind farms using series dynamic braking resistors (March 2007)," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 966–975, Aug. 2007.

[174] W. Freitas, A. Morelato, and W. Xu, "Improvement of induction generator stability using braking resistors," *IEEE Trans. Power Syst.*, vol. 19, no. 2, pp. 1247–1249, May 2004.

[175] R. M. Kamel, "Three fault ride through controllers for wind systems running in isolated micro-grid and effects of fault type on their performance: A review and comparative study," *Renew. Sustain. Energy Rev.*, vol. 37, pp. 698–714, Sep. 2014.

[176] S. B. Naderi, M. Negnevitsky, A. Jalilian, and M. T. Hagh, "Fault ride through improvement of fixed speed wind turbine using CR-FCL with its modified control strategy," in *Proc. Australas. Univ. Power Eng. Conf. (AUPEC)*, Sep. 2016, pp. 1–6.

[177] S. B. Naderi, M. Negnevitsky, A. Jalilian, M. T. Hagh, and K. M. Muttaqi, "Optimum resistive type fault current limiter: An efficient solution to achieve maximum fault ride-through capability of fixed-speed wind turbines during symmetrical and asymmetrical grid faults," *IEEE Trans. Ind. Appl.*, vol. 53, no. 1, pp. 538–548, Jan./Feb. 2017.

[178] M. Firouzi and G. B. Gharehpetian, "A modified transformer-type fault current limiter for enhancement fault ride-through capability of fixed speed-based wind power plants," in *Proc. Conf. Elect. Power Distrib. Netw. Conf. (EPDC)*, Apr. 2017, pp. 33–38.

[179] M. Firouzi and G. B. Gharehpetian, "Improving fault ride-through capability of fixed-speed wind turbine by using bridge-type fault current limiter," *IEEE Trans. Energy Convers.*, vol. 28, no. 2, pp. 361–369, Jun. 2013.

[180] M. I. Marei, H. S. K. El-Goharey, and R. M. Toukhy, "Fault ride-through enhancement of fixed speed wind turbine using bridge-type fault current limiter," *J. Elect. Syst. Inf. Technol.*, vol. 3, no. 1, pp. 119–126, 2016.

[181] G. Rashid and M. H. Ali, "A modified bridge-type fault current limiter for fault ride-through capacity enhancement of fixed speed wind generator," *IEEE Trans. Energy Convers.*, vol. 29, no. 2, pp. 527–534, Jun. 2014.

[182] L. Ye and L. Z. Lin, "Study of superconducting fault current limiters for system integration of wind farms," *IEEE Trans. Appl. Supercond.*, vol. 20, no. 3, pp. 1233–1237, Jun. 2010.

[183] D. Ramirez, F. Martinez-Rodrigo, S. de Pablo, and L. C. H.-de Lucas, "Assessment of a non linear current control technique applied to MMC-HVDC during grid disturbances," *Renew. Energy*, vol. 101, pp. 945–963, Feb. 2017.

[184] O. Noureldeen, M. Rihan, and B. Hasanin, "Stability improvement of fixed speed induction generator wind farm using STATCOM during different fault locations and durations," *Ain Shams Eng. J.*, vol. 2, no. 1, pp. 1–10, 2011.

[185] H. Heydari-Doostabad, M. R. Khalghani, and M. H. Khooban, "A novel control system design to improve LVRT capability of fixed speed wind turbines using STATCOM in presence of voltage fault," *Int. J. Elect. Power Energy Syst.*, vol. 77, pp. 280–286, May 2016.

[186] M. M. A. Mahfouz and M. A. H. El-Sayed, "Static synchronous compensator sizing for enhancement of fault ride-through capability and voltage stabilisation of fixed speed wind farms," *IET Renew. Power Gener.*, vol. 8, no. 1, pp. 1–9, Jan. 2014.

[187] W. Zhu and R.-F. Cao, "Improved low voltage ride-through of wind farm using STATCOM and pitch control," in *Proc. IEEE 6th Int. Power Electron. Motion Control Conf.*, May 2009, pp. 2217–2221.

[188] J. A. Suul, M. Molinas, and T. Undeland, "STATCOM-based indirect torque control of induction machines during voltage recovery after grid faults," *IEEE Trans. Power Electron.*, vol. 25, no. 5, pp. 1240–1250, May 2010.

[189] M. Narimani and R. K. Varma, "Application of static Var compensator (SVC) with fuzzy controller for grid integration of wind farm," in *Proc. CCECE*, May 2010, pp. 1–6.

[190] R. M. M. Pereira, C. M. M. Ferreira, and F. M. Barbosa, "Comparative study of STATCOM and SVC performance on dynamic voltage collapse of an electric power system with wind generation," *IEEE Latin Amer. Trans.*, vol. 12, no. 2, pp. 138–145, Mar. 2014.

[191] J. Ren, Y. Hu, J. Wang, and Y. Ji, "Principle of low voltage ride-through ability realization of fixed speed wind generator using series reactor and SVC," in *Proc. 7th Int. Power Electron. Motion Control Conf.*, vol. 3, Jun. 2012, pp. 2173–2177.

[192] S. Kalsi, D. Madura, and M. Ross, "Performance of superconductor dynamic synchronous condenser on an electric grid," in *Proc. IEEE/PES Transmiss. Distrib. Conf. Expo., Asia Pacific*, Aug. 2005, pp. 1–5.

[193] D. T. Bradshaw, "'Super' reactive power for the power system through SuperVAr/spl trade/ high temperature superconductor dynamic synchronous condensers," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, vol. 2, Jun. 2004, pp. 2058–2061.

[194] M. Ross and S. Kalsi, "Applications of superconducting synchronous condensers in wind power integration," in *Proc. IEEE/PES Transmiss. Distrib. Conf. Exhibit.*, May 2006, pp. 272–277.

[195] S. Kalsi, D. Madura, R. Howard, G. Snitchler, T. MacDonald, D. Bradshaw, I. Grant, and M. Ingram, "Superconducting dynamic synchronous condenser for improved grid voltage support," in *Proc. IEEE PES Transmiss. Distrib. Conf. Expo.*, vol. 2, Sep. 2003, pp. 742–747.

[196] M. F. Farias, P. E. Battaiotto, M. G. Cendoya, and F. de Ingeniería, "Investigation of UPQC for sag compensation in wind farms to weak grid connections," in *Proc. IEEE Int. Conf. Ind. Technol.*, Mar. 2010, pp. 937–942.

[197] A. Moghadasi and A. Islam, "Enhancing LVRT capability of FSIG wind turbine using current source UPQC based on resistive SFCL," in *Proc. IEEE PES T D Conf. Expo.*, Apr. 2014, pp. 1–5.
[198] A. H. Moghadasi, A. Islam, and M. Amini, "LVRT capability assessment of FSIG-based wind turbine utilizing UPQC and SFCL," in *Proc. IEEE PES Gen. Meeting Conf. Expo.*, Jul. 2014, pp. 1–5.
[199] M. Ferdosian, H. Abdi, and A. Bazaei, "Improving the wind energy conversion system dynamics during fault ride through: UPFC versus STATCOM," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2015, pp. 2721–2726.

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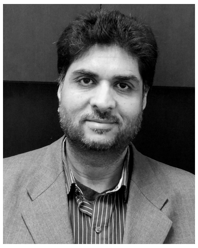

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