A Review of Power Electronic Converters for Variable Speed Pumped Storage Plants: Configurations, Operational Challenges, and Future Scopes

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***Abstract*—Pumped storage power plant has gained a high level of attention in recent years, mainly because of its ability to act as a large-scale energy storage option and to improve power system flexibility. Doubly fed asynchronous machine with the partially rated power electronic converter is adopted in pumped storage plants to provide variable speed operation and improve energy efficiency. This paper summarizes the power converter topologies in large rated variable speed pumped storage plant (VSPSP), also covers the suitability of each converter topology, modulation techniques, and parallel converter schemes. Also, it presents operational issues of the parallel converter system in VSPSP such as the shutdown of the plant due to insufficient converter redundancy and lack of fault-tolerant control schemes, a power outage due to the inadequacy of converter protection system, and unbalanced power sharing due to circulating current. Furthermore, the reliable mitigating/additional techniques are discussed for future research. It concludes that the refinement of these aforementioned issues will provide continuous operation of the plant.**

***Index Terms*—Doubly fed asynchronous machine (DFAM), hydropower generation, power converters, variable speed pumped storage plant (VSPSP).**

I. Introduction

SEVERAL possible technologies for electricity storage are developed including high energy batteries, flywheels, superconducting magnetics, compressed air, and pumped storage power plants (PSPPs). Among the mentioned technologies, PSPP is considered as a reliable and bulk energy storage system [1]. The PSPPs that are constructed in the beginning of the 20th century in the European continent were of fixed speed type employing synchronous machine and the same were continually established in Asian and American continents also. The total installed capacity of fixed speed PSPP in India is 4804 MW out of worldwide capacity of 130 GW [2]. However, the fixed speed PSPP [Fig. 1(a)] suffers from major drawbacks including: 1) inability to generate power over full range of water head and 2) reduced efficiency during partial generation and pumping modes of operation. The aforementioned drawbacks can be overcome by the transformation of PSPP from fixed speed mode to variable speed mode. In order to enable variable speed operation, synchronous machines of fixed speed PSPP need to be driven by power electronic converters with a rating equivalent to the rating of machine. Such a design of high capacity power electronic converter is not economical [3]. Furthermore, these full size converters ($>$200 MW) are very challenging in size, cost, and site clearance in the case of underground power houses. Therefore, variable speed PSPP employing doubly fed asynchronous machine (DFAM) is an acceptable option for the sites with wide variation in water head [4]. A 400-MW variable speed unit (with cycloconverters) is under operation at Ohkawachi since 1990 [5]. In India, the first variable speed PSPP having four numbers of 250-MW DFAM totaling to a capacity of 1000 MW is under construction at the Tehri Dam of Uttarakhand state [2]. The speed of machine (250-MW DFAM) was fixed at 230.77 rpm based on hydraulic studies conducted in Tehri pumped storage plant. Therefore, the design team has gone for DFAM with 26 poles to meet grid frequency. It is noted that a DFAM with 18 poles is serving in Goldisthal PSPP (Germany) at the rotational synchronous speed of 333 rpm [6].

Power converter redundancy and protection of power converter connected in rotor circuit are considered the most important operational challenges in DFAM-fed variable speed PSPP [7]. However, HVDC–voltage source converter (VSC) stations rated about 500 MW (between Ireland and Great Britain, operating at $\pm$200 kV, 2012) are in action and redundancy in these power converter stations is not an immense issue [8]. But, it is experimented/noted that multichannel power converters connected in the rotor circuit of DFAM produce over voltage in rotor windings during the operation of breakers/contactors, placed in each channel of converters, which causes insulation failure. Also it is known that, voltage rating of DFAM rotor circuit is much lesser than stator due to the usage of slip rings (typical 250-MW DFAM rotor windings are $\sim$4.8 times lesser voltage handling capabilities than stator).

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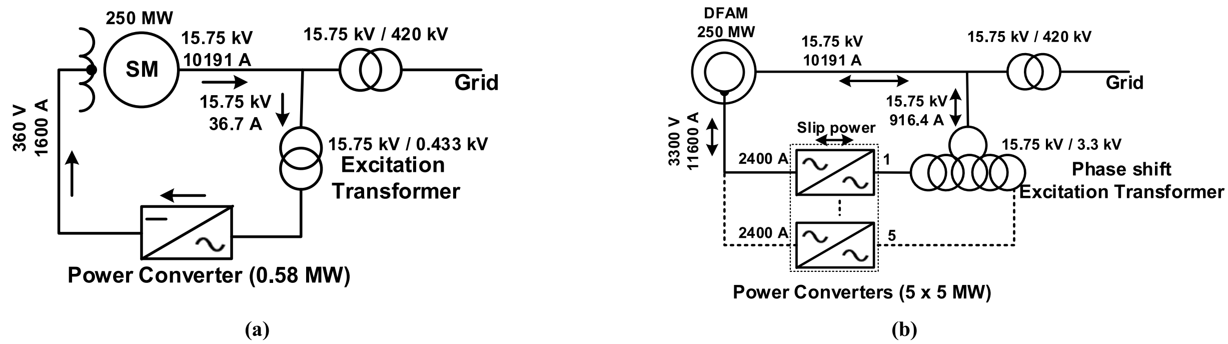

Fig. 1. Machines serving to a typical 250-MW hydro generating unit. (a) Synchronous machine. (b) DFAM.

DFAM is also widely used in wind power generating systems (WPGS) [9]–[11]. Issues on power redundancies (possibilities of overvoltage in rotor windings), protection of power converters (dynamic variation of rotor frequency and detection of dc component rotor current) are also applicable to WPGS [7]. However, the rating of DFAM used in WPGS (maximum of 8 MW [10]) is much lesser in comparison with variable speed PSPP (e.g., 400 MW [5]). In addition, stoppage of one machine in wind farm does not make any impact on the stability of power grid. Furthermore, it is mandatory to have power and control redundancies in large rated hydro power plants (>100 MW) according to the country's electricity authority, e.g., Central Electricity Authority (India) [12]. Unlike WPGS, DFAM is operated as motor in variable speed PSPP which has a dedicated control system for starting of pump turbine.

In consideration of operational issues in DFAM (>100 MW of unit capacity) mentioned before, brushless DFAM is an alternative for variable speed PSPP. However, it is not preferred for large rated PSPP in view of quick voltage regulation and large amount of reactive power support [13]–[15]. As far as author's knowledge, brushless DFAM is not yet installed or planned for large rated PSPP in any part of the world. Hence, this paper focuses only on DFAM serving to variable speed PSPP. High amount of current in rotor circuit of DFAM through brushes and slip rings seems to be challengeable due to: 1) operating temperature and 2) brush voltage drop. However, it is practically acceptable in presently available technology, e.g., a 400-MW Ohkawachi (Japan) hydrogenating unit with rotor currents of 12 670 A and a 300-MW Goldisthal (Germany) hydrogenating unit with rotor currents of 8970 A are currently in operation [5], [31].

The schematic of DFAM-fed variable speed PSPP is shown in Fig. 1(b). The power electronic converters are connected in rotor circuit of the DFAM, there by acting as ac excitation system of the machine. The main advantage of such scheme is the requirement of the power electronic converter with rating equivalent to slip power, normally, will be a fraction of the machine rating (typically about 10%–25% of machine rating) [16]. The principle of operation of DFAM-based PSPP is depicted in Table I, which is similar to the wound rotor induction machine (mutual induction principle) whereas the stator circuit is directly connected to grid and rotor circuit (three-phase cylindrical winding) is also connected to grid through back-to-back power converters. Magnitude and frequency of rotor currents are controlled for adjustable real (speed) and reactive power delivery [17]. The plant is able to operate in three modes, namely, synchronous, supersynchronous, and subsynchronous allowing the optimum energy transfer from source to load (motoring), and vice-versa (generating). This type of plants helps in improving power controllability, grid balancing, increase energy efficiency, and power quality in grid networks [18].

TABLE I
PRINCIPLE OF OPERATION OF DFAM

Mode of Operation	Speed	Stator Power	Rotor Power	Frequency
Subsynchronous Motoring	$\omega_s > \omega_r$	Positive	Negative	$F_s = \frac{\omega_r * p}{120} + F_r$
Supersynchronous Motoring	$\omega_s < \omega_r$	Positive	Positive	$F_s = \frac{\omega_r * p}{120} - F_r$
Subsynchronous Generation	$\omega_s > \omega_r$	Negative	Positive	$F_s = \frac{\omega_r * p}{120} + F_r$
Supersynchronous Generation	$\omega_s < \omega_r$	Negative	Negative	$F_s = \frac{\omega_r * p}{120} - F_r$

Positive – Power Flow From Grid To Machine ω_s - Synchronous speed
Negative – Power Flow From Machine To Grid ω_r - Rotor speed
F_s – Stator frequency F_r – Rotor frequency   p – no.of poles

The application of semiconductor devices in DFAM-fed variable speed PSPP ranges from naturally commutated devices (Thyristor) to self-commutated devices (Insulated Gate Bipolar Transistor (IGBT), Injection Enhanced Gate Transistor (IEGT), etc.,) depending on the requirements such as switching characteristics, ease of gate control, reliability, low on state power losses, and voltage drop [19], [20]. In a similar way, the advancement in power converter topology ranges from cycloconverter to multilevel VSCs to achieve rotor current harmonic distortion reduction, pure sinusoidal supply, etc. In a situation where in the semiconductor devices ratings are limited, it is preferred to employ parallel converters to share the rotor circuit current [21]. Under the availability of water head and grid supply, the power electronic converters primarily dictate the continuity of operation of the DFAM-fed variable speed PSPP. It is to mention that the power converter redundancy is not yet adopted in any of the commissioned variable speed PSPPs due to the occurrence of high voltage in rotor windings while interrupting the circuit through contactors

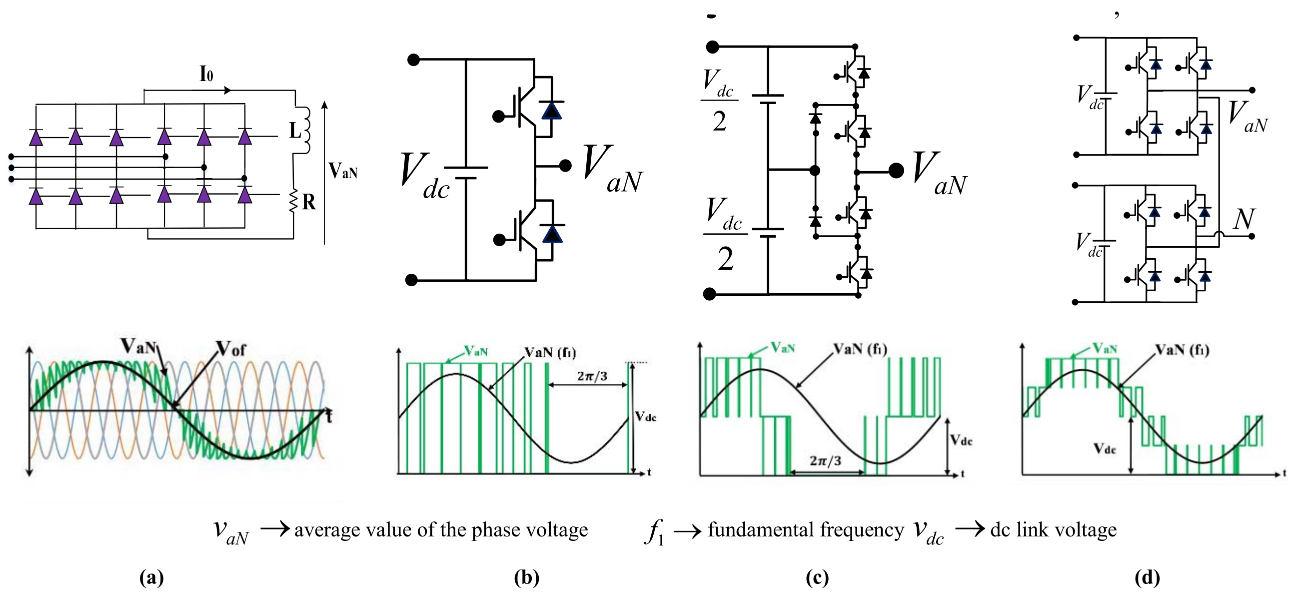

Fig. 2. Power converter topologies and their voltage waveforms. (a) Cycloconverter [30]. (b) 2L-VSC [42]. (c) 3L-NPC VSC [42]. (d) 5L-CHB VSC [42].

during power converter faults. Therefore, faults occurred in power converter result shutdown of particular unit of the plant [7]. Such unscheduled stoppage of the plant threatens the grid security. On recognition of these facts about the power electronic converters employed in variable speed PSPP, a timely attempt is made to present about the operational issues of the power converters in DFAM-fed variable speed PSPP.

This paper provides a comprehensive review of the power converter topologies, parallel converters schemes and their availability in variable speed PSPP equipped with the DFAM. Moreover, operational issues of the parallel converter in large rated variable speed pumped storage plant (VSPSP) is summarized and assessed with simulation and experimental results. Based on aforementioned scenarios, the organization of the succeeding script as follows: Sections II and III summarize the converter topologies and modulation techniques used in variable speed PSPP, respectively, also, adoptability of each converter topology in PSPP station is specified. The need of parallel converters configuration and schemes are considered in Section IV. Section V summarizes the operational issues of the power converter linked to the reliability and Section VI provides the simulation and experimental results of these operational issues in large rated DFAM-fed variable speed PSPP. Section VII introduces the suitable techniques for mitigating the operational issues of the power converter as future research. Concluding remarks are summarized in Section VIII.

II. Power Converters Employed in DFAM-Fed Variable Speed PSPP

Power converters play an important role in DFAM-fed variable speed PSPP by facilitating variable speed operation, smooth starting, braking (regenerative and dynamic), reactive power compensation and also acting as active power filters. Moreover, the converters are also responsible for achieving real and reactive power control in generation mode and speed and reactive power control in the pumping mode [17], [22], [23]. The different power electronic converters that are employed in variable speed PSPP are presented below.

A. Load-Commutated Inverters

Load-commutated inverters (LCIs) are employed in the fixed pumped storage plants driven by synchronous machines are in operation with the rating of 50–100 MW range [24]. Due to lack of reactive power control, current distortion, and low power factor, these inverters are not recommended for DFAM-fed variable speed PSPP [25]. It is also to mention that the installation of LCI-fed DFAM in variable speed PSPP is not yet adopted in any of commissioned PSPP.

B. Matrix Converter

Matrix converter-fed DFAM used in wind power system is discussed in [26] and [27]. However, back-to-back converter topologies are preferred in such systems than matrix converters due to: 1) output voltage stepup capability; 2) unconstrained reactive power compensation; 3) simple feedback control of the input currents independent of the output currents; and 4) single-phase operation capability [28]. In addition, considering the system operation under faulty conditions (open circuit fault), back-to-back converter seems to be a preferred option in industrial drives as it allows the process to continue even at open circuit faults in rectifier side, i.e., ac–dc conversion stage [29]. Also, high power density and power-to-mass ratio are questionable in large rated, low switching frequency applications equipped with matrix converter [29]. In view of this, matrix converters fed large rated DFAM is not yet adopted in any of commissioned PSPP [30].

C. Cycloconverters

Cycloconverter [shown in Fig. 2(a)] is a type of power electronic converter which provides variable ac voltage of variable frequency without dc link. Such type of converter employing gate turn-OFF thyristors was adopted in the hydroelectric variable speed plants at Ohkawachi power station in Japan [31] and Goldisthal power plant in Germany [32]. The merits of cycloconverter over LCI are: 1) generation of low-frequency ac voltage; 2) instantaneous real and reactive power control; and 3) low on state power losses. However, the cycloconverters suffers from demerits including: 1) inability to generate output voltage with a frequency greater than input frequency; 2) requirement of additional static frequency converter (SFC) during starting in pump mode; 3) high distorted rotor current in DFAM, thereby introducing the large size of filters compare to VSC's; and 4) reactive power absorption from grid in rotor side [32], [33]. The preferable number of switching devices used in cycloconverter is 72 (Conventional 12-pulse cycloconverter cascade) [31] for the minimum distorted required rotor current waveform (adopted in Ohkawachi power station, Japan), however, the number of switching devices shall be increased as per the higher pulse numbers to achieve better quality of rotor current, which leads to increase in size and cost of the converter.

D. Back-to-Back Voltage Source Converters

Back-to-back VSCs are the converters which has widespread applications including the control of DFAM-based variable speed PSPP [34]. Such converters have an ability to provide variable voltage and variable frequency supply during starting of the machine resulting the reduction of startup transients and energy losses [22]. Also, VSC with suitable control technique finds applications in power conditioning circuits such as STATCOM (reactive power compensation) and active power filters (elimination of harmonics). The main advantage of VSC is its ability to offer decoupled control of real and reactive power with a significant reduction of load current harmonics. The following are different types of VSC that are used DFAM-fed variable speed PSPP.

1) Two-Level Voltage Source Converter: This converter [shown in Fig. 2(b)] comprises six numbers of (three-phase) IGBT or GCT switch with a freewheeling diode across each switch. The merits of this converter are: 1) simple converter topology and control scheme; 2) active and reactive power control; 3) independent control of grid-side and machine-side converter; 4) no need of auxiliary devices for startup application in pumping mode; and 5) unity power factor at grid side [34]. The demerits are: 1) due to cross-influence of d- and q-axis, multivariable controllers are required for grid-side and machine-side converter; 2) high THD, high dv/dt, high harmonic losses compare to multilevel VSCs; and 3) possibility of predominant harmonic injection into the grid depending on the pulse width modulation (PWM) carrier frequency. The Frades II variable speed pumped storage hydropower plant (Portugal) has employed 2L-VSC [35].

2) Three-Level Neutral Point Diode Clamped VSC: This type [shown in Fig. 2(c)] of VSC belongs to multilevel converter family, in which odd number of levels are achieved due to the availability of the neutral clamp structure. This converter is maturely applied in large rating drives due to the lesser voltage stress on devices, resulting in the reduction of failure rate in semiconductor devices and generation of resultant waveform with better spectral performance [36]. Further, THD in rotor current is lesser than cycloconverter and 2L-VSC which leads reduction of filter size in 3L-NPC. [37]. The drawbacks of this converter type of VSC are: 1) requirement of additional clamping diodes which increase the size and cost of the system; 2) nonuniform power loss distribution among switches due to switching logic; 3) complex control system compared to that of 2L-VSC; and 4) voltage imbalance problem in dc link capacitor due to clamping diodes [38]. This type of VSC is employed in variable speed PSPP at Linthal, Switzerland. Also, Tehri Hydropower Development and Corporation (THDC India Ltd) is planning to install 3L-NPC in stage III project of Tehri Dam.

3) Cascaded H-Bridge Multilevel Converter: This converter [shown in Fig. 2(d)] circuit is having a special arrangement with PSTs (phase angle 15°) employed for the input line current/voltage THD improvement and common mode voltage mitigation [39]. The major advantages of such converter include: 1) very low rotor current THD, thereby requiring lesser cost and small size rotor side filters compare to 3L-NPCs; 2) identical phase connections leading to optimized circuit layout; 3) elimination of clamping diodes; and 4) the output voltage waveform nearer to sinusoidal. However, the cost of this converter is very high due to the requirement of PST and associated cabling needs. In China at Xiang Hong PSPP, CHB is adopted in startup applications of the synchronous machines-fed pumped storage plant [40].

4) Flying Capacitor Multilevel Converters: The number of switching devices used in this topology is reasonable and the use of dc link capacitors provides more flexibility. The voltage imbalance problem can be reduced by selecting proper switching technique of charging and discharging of capacitors [41]. The most important advantage of FC-MLC is low rotor current THD, improved power quality, and capacitor voltage balance. In addition, precharging of capacitors is necessary and sometimes it is difficult [42]. These converters are mostly used in static compensators and active filters in PSPP's. The summary of different types of VSCs is also presented in Table II.

III. Converter Modulation Techniques for Variable Speed PSPP

The key factors to be considered while formulating the modulation technique in power converters are: 1) minimization of utility line harmonics; 2) minimization of load current harmonics; 3) good utilization of dc link voltage; 4) minimization of switching frequency and losses; 5) uniform switching losses; and 6) uniform switching frequency for all switching devices; and 8) voltage balance in dc link capacitor [43]. The following are the different modulation techniques adopted in variable speed PSPP applications.

A. Sinusoidal PWM

In electric drives, SPWM is the widespread modulation scheme used in power converter control [44]. In this technique, the low frequency modulating signal (sinusoidal wave)

TABLE II

COMPARISON OF CONVERTER TOPOLOGIES (USED IN DFAM-BASED VSPSP > 200 MW)

	Cycloconverter [31],[32],[33],[35]	2L – VSC [34], [35]	3L – NPC [36],[37],[38]	3L – CHB – VSC [39],[40]	3L - FC – VSC [39],[41],[42]
No.of power Switches (IGBT + Diode)	72 *	12 +12	24 + 36	24 + 24	24 +24
dv/dt voltage stress	Very high	high	low	Very low	Very low
THD in rotor current**	0.582 %	0.482 %	0.449%	0.283 %	~0.3%
Size of filters	Very high	High	Moderate	Compact	Compact
Cost of filter	Very High	High	Reasonable	Low cost	Low cost
Fault tolerant capability	No	No	No	Yes	Yes
Advantages	No intermediate DC link required	Simple structure , Few no.of power devices	High efficiency at increased switching frequency	Equal loss distribution, Less common mode voltage	good performance for high and low modulation index
Disadvantages	requirement of additional SFC during starting in pump mode, reactive power absorption from rotor side grid	High switching losses, Efficiency and technical requirements are difficult to fulfill	Clamping diodes requirement, unequal power loss distribution in switches, DC-link balancing	More DC sources required	The increase in capacitors leads to more costs and space
Employed	Ohkawachi power station, Japan	Frades II variable speed pumped storage hydropower plant, Portugal	Linthal variable speed pumped storage plant, Switzerland	Xiang Hong PSPP, China	Used as static compensators

* Conventional 12-pulse Cyclo-converter cascade.

** based on the simulation of 230MVA DFAM in SIMSEN software [33].

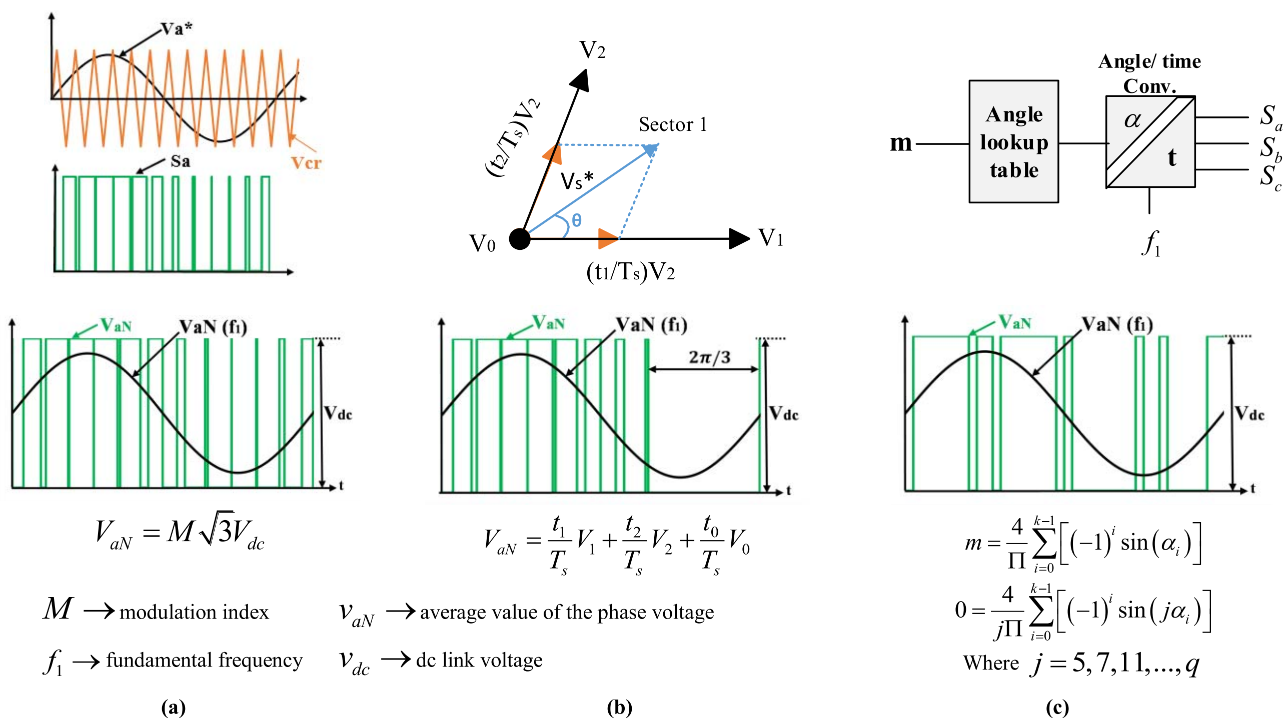

Fig. 3. Operating waveform for modulation techniques for 2L-VSC [43]. (a) SPWM. (b) SVM. (c) SHE-PWM.

is compared with the high frequency (switching frequency) carrier signal (triangular wave) in a logic device that provides PWM pulses, which in turn control the switching devices. The amplitude and frequency of converter output voltage depend on the modulating wave amplitude and frequency, respectively, [45]. The output voltage waveforms and equation are shown in Fig. 3(a). The maximum value of modulation index selected for SPWM in large rated electric drives is 0.7885 [39] and the value of switching frequency is limited to less than 1.5 kHz [46], [47] considering semiconductor

TABLE III
COMPARISON OF MODULATION TECHNIQUES (USED IN DFAM BASED VSPSP > 200 MW)

	Third Order Injection SPWM [25], [30]- [33]	SVC [19], [25], [34],[36], [37]	SHE – PWM [21], [25], [38] - [40]
Modulation Index	0.7855	0.907	0.83 [89]
Engaged	Smooth starting	Real and reactive power control	Active power filters
DC bus utilization	86.6%	86.6 %	86.6%
Maximum line- line voltage	0.707 Vdc	0.707 Vdc	0.707 Vdc
Switching frequency	~ 1.5 kHz [25]	250 Hz to 500 Hz [19]	< 1kHz [25]
Principle	Carrier based Sine-triangle modulation	Space vector theory	Frequency switching theory
Switching losses	high	moderate	less
Dynamic control response	moderate	high	low
Advantages	Easy implementation	precise control of the dc and ac current magnitude and phase	superior sinusoidal current waveform with a lower value of switching frequency
Disadvantages	Low output voltage	high level computational works required	Low dynamic response

losses and filter requirements for the large rated converters. However, the third-harmonic injection in the modulating wave can be utilized to ensure better utilization of dc link voltage in the high rated plant [20]. SPWM strategy is commonly used in starting of the DFAM-fed variable speed PSPP (pumping mode) [48], [49].

The selection of dc link voltage for SPWM

$$V_{\text{bus}} = V_{\text{out}}/\left(\sqrt{\left(\frac{2}{3}\right)}.2.M\right) \tag{1}$$

where M is the modulation index.

B. Space Vector PWM

SVM technique is derived from space vector theory and generates modulation signal according to the switching sector and angle. Basically, it produces the acting and null vectors based on the level of converters, which decide the switching of power devices [51]. The output voltage waveforms and equation are shown in Fig. 3(b). Compared to universal SPWM, space vector modulation utilizes 15.4% additional dc supply [51]. In addition, SVM fired converters generate waveforms with less THD in rotor current and also suitable for fast dynamic response application [52]. Moreover, it can accommodate maximum modulation index (0.907) and provide less switching losses [53]. The dynamic control of real and reactive power in variable speed PSPP is desirable through SVM for low switching frequency operation, e.g., Linthal variable speed PSPP, Switzerland.

The selection of dc link voltage for SVM

$$V_{\text{bus}} = V_{\text{out}}/\left(\sqrt{\left(\frac{2}{3}\right)}.\sqrt{3}.M\right). \tag{2}$$

C. Selective Harmonic Elimination PWM

This PWM technique is framed based on frequency switching theory. The main advantage of this technique is that the harmonics of higher order (e.g., 11, 13, 17, etc.) can be eliminated by selecting the switching angle corresponding to the harmonic order as per predetermined lookup table [54], [55]. The output voltage waveforms and equation are shown in Fig. 3(c). In general, Newton–Raphson iteration method is used to formulate the lookup table. Due to the elimination of higher order harmonics it is possible to obtain superior sinusoidal output waveform with a lower value of switching frequency comparatively. This technique is widely used in active power filters. However, the dynamic response of the converter in closed loop control is low due to the prespecified values [56], [57]. Due to selective harmonic elimination capability, this PWM technique finds application as active power filters in variable speed PSPP. The summary of different types of modulation techniques is also presented in Table III.

IV. PARALLEL OPERATION OF CONVERTERS IN VARIABLE SPEED PSPP

Due to the limitation in the semiconductor device rating, it becomes difficult to design a single converter for large power ratings. In such a situation parallel converters can be adopted to share high power in rotor circuit of the machine. The main criteria for the parallel operation of converters are that the output voltage of all converters connected in parallel should be equal in amplitude, frequency and phase. In such a configuration it is possible to have equal/unequal power sharing depending on the power rating of each converter. The application of parallel converter results in improvement of reliability, flexibility, and power quality of the plant. Further, the parallel converter operation increases the efficiency of the plant as the participation of each converter can be controlled depending upon the output requirements [58]–[60]. A typical parallel converter is driven DFAM-fed variable speed PSPP shown in Fig. 4.

A. Power Sharing in Parallel Converters

In general: 1) passive current sharing; 2) droop control method; and 3) active current sharing methods are utilized for

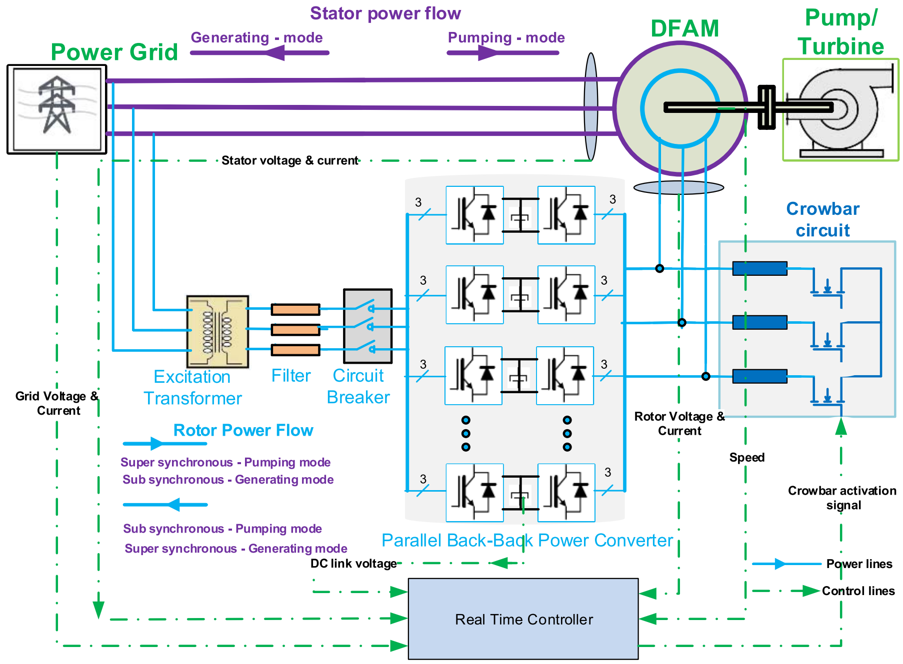

Fig. 4. Parallel converters serving to DFAM-fed Variable speed PSPP.

the effective power/current sharing in parallel converters. Passive current sharing and droop control methods deal with low power circuits including uninterruptable power supplies (UPS) and islanded micro grid applications. Master–slave control used in active current sharing method is also preferable for UPS applications [61]–[65]. Hence, these methods are not discussed in this paper as it focuses on large rated power converters serving in variable speed PSPP.

The active current sharing method is most suitable for the parallel converters in large rated variable speed PSPP. In active current sharing method, each converter to be connected in parallel is connected by wired communication. A control system is developed to generate the reference current for power sharing [66], thereby eliminating the need of large impendence for current sharing. Depending upon the control the following are the different types of active current sharing methods.

1) Central Limit Control: In this configuration [Fig. 5(a)], the number of converters is preknown and each converter is of same rating/topologies. Depending upon the load current requirement, the central control system sends a signal to each converter for sharing the load current. However, such scheme is less reliable due to the fact that the failure of any one converter renders the system to a standstill [67], [68].

2) Circular Chain Control: In this method [Fig. 5(b)], the converter controls are formulated in the circular configuration, wherein, each converter tracks the power of the preceding converter to achieve equal current sharing of the load [69]. This chain control requires more communication wires in between the converters and hence making the control complex. In addition, the implementation of redundant converter operation is not easy [70].

3) Active Current Distributed Logical Control: In this method [Fig. 5(c)], there are two types of controllers are employed, namely, individual controller and coordinated controller. Coordinated control systems track the load current and give the reference current to the individual controller of each converter, which in turns regulates the sharing of load current. In addition, the individual controller is designed with a capability to limit the circulating and harmonic currents in parallel converter configuration [71]. The merits of this method are: 1) the converter of different rating and topologies can be connected in parallel; 2) extension of parallel converter is simple; 3) isolated/redundant operation of converters are possible; 4) for low power application it is possible to select the required number of converters in parallel configuration; and 5) no need of external fault monitoring and detection schemes as in-build controller can identify defective converter [72].

B. Circulating Current in Parallel Converters

Circulating current is an important issue in the parallel connected converters during the sharing of current between them. These circulating currents are formed due to: 1) unbalance impedance in phases of the converter; 2) characteristic of the converter components; and 3) asynchronous switching operations [73]–[75]. The following are the schemes used to reduce the circulating currents in parallel converters.

1) Phase Shift Transformers: The provision of phase shift transformer (PST) in parallel converters is used to prevent the common mode over voltage and suppressing the circulating current by designing with certain turn's ratio and phase shift [76], [77]. These PST's are also used to reduce the line current harmonics e.g., Linthal variable speed PSPP, Switzerland (2011), PST vector group is Yd1 ($-12°$) d1 ($-6°$) d1 ($0°$) d1 ($+6°$) d1 ($+12°$). In olden days (1995s), dc choke had been used to suppress the circulating current [18] in variable speed

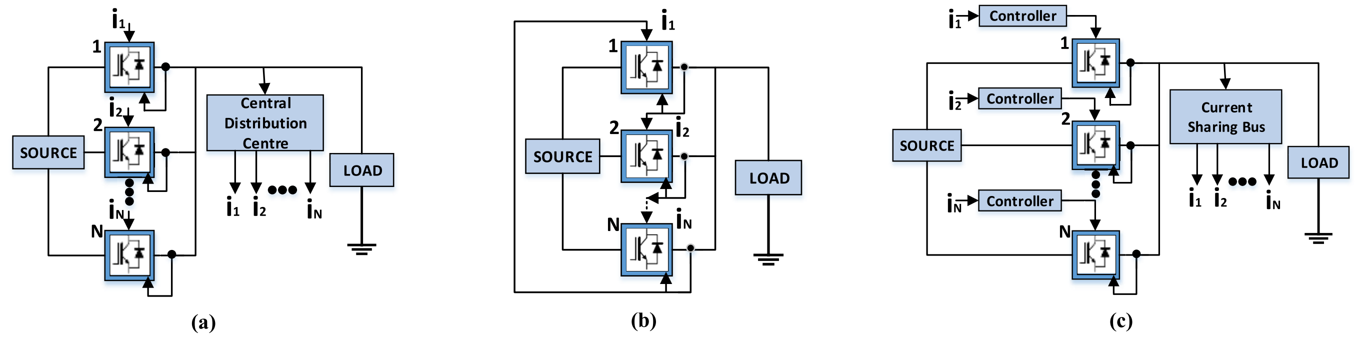

Fig. 5. Parallel converters control strategies. (a) Central limit control [68]. (b) Circular chain control [70]. (c) Active current distributed logical control [71].

PSPP instead of PST's. e.g., 300-MW Goldisthal variable speed PSPP, Germany.

2) Space Vector Modulation: The interleaved PWM with discontinuous space vector modulation techniques can be used to reduce circulating currents. The interleaving techniques, maximizes the cancelation of harmonics between parallel modules, thereby reducing the filtering requirements [78].

3) Individual Voltage Oriented Control: This techniques can be used to eliminate the circulating current in the respective power converter module. An each module having its own modulator and controller with the closed loop system [79]. This independent regulation of each parallel module is adjusted the zero-sequence voltage to restrain the circulating current [80], [81]. Each power module has its own modulator and controller which makes system expandable to any number of modules in parallel.

In summary, PSTs with multichannel VSCs are preferable in rotor circuit of DFAM in variable speed PSPP. This setup offers reduction in line current harmonics and maintain unity power factor of the system. Starting of pump turbine at motoring mode of operation is done by energizing rotor circuit through power converters. The stator circuit is short circuited while starting. Active current sharing method is desirable in multichannel power electronic converter-fed large rated hydrogenating unit. Space vector modulation with less switching frequency (300–500 Hz) is widely used in such units for real and reactive power control. The operational issues of such multichannel power converter fed-DFAM are explained in Section V.

V. Operational Issues of Power Converters in Variable Speed PSPP

In fixed speed pumped storage plants, thyristor-based power electronic converters are used in the excitation system (dc) having a lower power rating in comparison with machine rating (Ex: For a typical 250-MW synchronous machine, the excitation system needs around 0.58 MW of power, i.e., 0.23% of the machine capacity). In addition, the failure rate of the thyristor is low and it can handle high power compared to self-commutated power semiconductor devices. Moreover, the power converters are not much affected by the stator side grid disturbances (voltage drop, short circuit, and frequency drop) due to the design of the synchronous machine. Therefore, the protection of the converter is not much complicated and the ability to fault ride through in plant is easygoing. Furthermore, providing redundancy in both power and control circuits is also easy in case of a fault in converter module, as the power handling of the converter is less. In Tehri (India) hydropower plant (Phase I), redundancy is ensured by means of two fully automatic power converter units with independent control.

On the other hand, the rating of excitation system (ac) equipped with power electronic converter is quite large in DFAM-fed variable speed PSPP which handles slip power of the machine [Ex: For a typical 250-MW DFAM with the target of $\pm 10\%$ speed variation, power converters need to handle 25 MW (slip power) of power with the current rating of 11 600 A]. Due to the high power rating requirement, there is a critical necessary to opt for the parallel operation of converters in DFAM-fed variable speed PSPP. The self-commutation switches (IGBT, IEGT, etc.) can be used as switching devices in view of better sinusoidal rotor current and minimizing the harmonics.

The operational issues associated with the power converters serving DFAM-fed variable speed PSPP's are as follows:

A. power redundancy during the converter fault;
   1) contactor used in series with each power converters in parallel converter system;
   2) detection of dc component during a fault;
B. control redundancy;
C. deficiency in the protection of power converter;
D. circulating current in parallel converters;
E. operating at synchronous speed.

Each operational issue is presented in detail below.

A. Power Redundancy During the Converter Fault

Around 38% of failure in an electric drive is due to the faults occurred in power converters which includes power devices failure, dc link capacitor failure, and driver circuit failure [82]. In power converters, open and short-circuit faults are due to: 1) electromagnetic interference; 2) malfunction in the driver circuit; 3) rapid voltage dip/swell; 4) auxiliary power supply failure; and 5) avalanche stress, and temperature overshoot in power devices [83], [84]. Moreover, if any disturbances (voltage drop, short circuit) occur in the stator circuit, results in higher current/voltage in the rotor circuit, which easily affects the power converter connected in the rotor circuit of the machine.

In addition, a typical fault in converter circuit (without redundant converters) employed in variable speed PSPP may result in stopping of the plant for more than 8 h, leading to huge financial losses. To illustrate, consider a plant having five units with each unit rated at 300 MW. If a converter fault at any one unit results in stopping of a unit for 8 h, the estimated financial losses will be U.S. \$176 560/fault/unit (considering U.S. \$0.07/kWh). Further, if it is assumed that every unit encounters a fault per year, the estimated financial losses of the plant will be U.S. \$882 800/plant/year. The assumption of one fault per year was taken by considering: 1) IGBT triggering circuit failure rate is 0.96 failure per year (i.e., 1 failure occurs at 1.04 years) [85]; 2) motor drive failure rate is 0.27 failure per year (i.e., 1 failure occurs at 3.7 years) [86]; and 3) IGBT failure rate is 500 FIT (1 FIT equals 10^{-9} failures per hour) [87], [88]. It is noted that the probability of failure of power converter serving in PSPP is high as it has more than 300 power devices (IGBT and Diode) [36].

In order to overcome the power converter failure, redundancy phenomena need to be incorporated so as to allow for the sustained operation of the plant. In India, the Central Electricity Authority has mandated that all the hydropower plants having rating more than 100 MW must have power and control redundancy in excitation circuit [12]. However, there is no redundancy in any of the practical parallel converter system-fed DFAM-based variable speed PSPP in the world. Generally, providing contactors/ mechanical breaker connected in series with each converter is a solution to have redundancy. This contactor can be connected in either dc side or ac side of the converter. The following issues are identified when contactors are considered for the isolation of converters in the high rating plant.

1) Contactor Used in Series With Each Power Converters in Parallel Converter System: The contactors connected in series with the power converter produces triangular transient recovery voltage (TRV) (high amplitude and high frequency of short duration) during interruption of the fault current in the high power rated circuit [89], [90]. This very high steep voltage causes the insulation of the rotor winding of the DFAM to be stressed and can result in breakdown. This rapid change in the voltage has deleterious effects on the power devices and sometimes this will also affect the healthy converters that are in service. The developed transient voltage is given by (3). Moreover, provision of contactors increases the risk and maintenance related issues in the high rated plant [91], [92]. Hence, this contactor configuration is not preferred for redundant operation of the converter

$$V_{\mathrm{TRV}} = \sqrt{2} I_f \omega L_{\mathrm{eq}} \left[(1 - e^{-\alpha t}) \left(\cosh \beta t + \frac{\alpha}{\beta} \sinh \beta t \right) \right]$$

$$\alpha = \frac{1}{2 Z_{\mathrm{eq}} C_{\mathrm{eq}}} \quad \beta = \sqrt{\alpha^2 - \frac{1}{L_{\mathrm{eq}} C_{\mathrm{eq}}}} \quad \omega = 2\pi f \tag{3}$$

where

V_{TRV} transient recovery voltage across the breaker contacts;
I_f fault current magnitude (in kA rms);
Z_{eq} equivalent source impedance in ohms;
L_{eq} equivalent source inductance in henrys;
C_{eq} equivalent source capacitance in farads.

As per the standard ANSI/IEEE C37.013-1993, the acceptable level of TRVs for 10–50 MVA generator is 1.5 kV/μs during the interruption of circuit breaker and the production of peak voltage is 1.84 times rms value of maximum input voltage [93]. However, the maximum permissible rotor voltage is limited to 1.34 times rms value of the rotor voltage and the TRV rate is limited to 0.6kV/μs for considering the insulation of the rotor winding of a DFAM based variable speed unit [94]. Hence, the interruption of circuit breaker will definitely cause overburden to insulation used in rotor winding of DFAM and converter redundancy is challengeable.

2) Detection of DC Component During a Fault: During faults in the converter, due to the large time constants (high X/R) a current of high amplitude and very low frequency is produced, typically with the absence of zero crossing. The magnitude of dc component depends on fault current and fault inception in the cycle [95]. This high dc component can pose problems/challenges in diagnosis of fault current and interrupt difficulties. According to the standards IEC 62271-100 and IEEE C37.013-1997 that the interruption of current by a high-speed circuit breaker should be completed in not more than 40 ms, otherwise results in serious damage to the contactors and equipment [96], [97]. The detection of dc component and to break such a current during this fault by contactors is very difficult, prolonging the fault isolation process resulting in the damage of other converter modules due to the fault current. Moreover, a suitable circuit breaker break such a high dc component in power converter circuits is high challengeable [98], [99].

ALSTOM jointly with EPFL, Switcherland suggested a possible solution for detecting dc component or extremely low-frequency rotor current by using digital substation technology which incorporates Rogowski current transformers and resistive voltage dividers with IEC 61850-9-2 LE [7]. Nevertheless, the solution of these findings is not yet adopted in any of variable speed PSPP.

B. Control Redundancy

Field oriented vector control provides the good dynamic performance of the DFAM. This dynamic control works with the aid of controllers, sensors (speed, voltage, current, etc.), and accessories. These sensors and controllers can be affected by electromagnetic interferences, internal and external faults. Moreover, the complexity of the control circuit involving parallel converters, sensors, controllers, etc. will increase the chance of failure. Any failure in sensors at DFAM drive results to current transients in the rotor winding, produces grid disturbance in higher magnitude and decisive process of the machine is interrupted. In variable speed drives, 53% of faults [82] are due to control circuit failure, therefore, much attention needs to be given to the control circuit faults and provide possible redundancy/fault tolerance in the control circuit of large rated VSPSP. Furthermore, the power converters are precisely controlled with the suitable modulation techniques by the use of driver circuit. If any faults occur in driver circuit leads to open circuit fault in the converter, which in turn produces nonsinusoidal current waveforms. These waveforms introduce the thermal overstress on the power semiconductor devices resulting in a short-circuit fault [83], [84].

C. Deficiency in Protection of Power Converter

Rotor side power converter facilitates real and reactive power control in DFAM-fed variable speed PSPP. These converters are easily affected by grid disturbances and external faults. In general crowbar protection circuit is used for the protection of power converters and it is enabled based on the threshold value of dc link voltage [100]. This circuit is connected in rotor terminals of the machine in parallel with power converters. It consists of resistors and power switching devices to offer short circuited rotor at the time overvoltage experience by grid disturbances. The value of resistance is selected based on the dc link clamp effect and this resistance should be sufficiently high to limit the short-circuit current and low enough to avoid the high voltage while in operation [101], [102]. If any disturbances occur in the grid, then the value of dc link voltage will increase and crowbar protection circuit will come to operate. The crowbar circuit should not be turned ON for the transient faults (short term faults, switch ON/OFF of electrical equipment) and if it is triggered, the circuit gets to turn OFF when the transient is reduced. Hence, the self-commutating device (e.g., IGBT) is a better solution for the power devices in crowbar circuit [103].

Nowadays, crowbar protection is the only protection available for converters in variable speed PSPP. Once the crowbar protection is enabled, DFAM acts as the conventional induction machine (squirrel cage induction machine) and draws more reactive power from the grid causing voltage instability in the weak grid [104]. Therefore, the controller is instructed to stop the machine by enabling shutdown procedure in hydropower plants. To illustrate, consider a machine operating in generation mode at subsynchronous speed, during which compensation frequency is supplied by the power converter to get the synchronization frequency for the delivering power to the grid. The sudden removal of the power converter in this situation leads to the cutoff of compensation frequency, end up in delivering power with a different frequency in reference to grid frequency which results to instability in the machine. Hence, it is clear that the plant will get shut down as soon as crowbar protection acts. The aforementioned consequences do happen for even small disturbances occur in the grid (i.e., 0.05 p.u. depth voltage sag) and stoppage of the plant further increases. However, once the plant is shut down, it will take several minutes to get restarted leading again to high economic losses. In addition, the fault ride-through capability of the plant is a major problem in the aforementioned situations. Hence, additional protection is needed for the plant to increases the fault ride-through capability and thereby ensuring the continuity of plant operation.

D. Circulating Current in Parallel Converters

Circulating current is an important issue in the parallel connected converters. These circulating currents are more vulnerable to the high rated parallel power converters in large rated variable speed PSPP. Such circulating currents will distort the current waveforms, increase the losses and introduced unbalance currents in rotor side of the machine [75], [79]. DC chokes are employed in 300-MW Goldisthal variable speed PSPP to suppress the circulating current [18]. In addition, circulating current controller is also enabled in the vector control structure of the power converters. Also, it is to mention that the research has been continuously carried out to eliminate circulating current in large rated parallel power converters with better robust characteristics [105], [106].

E. Operating at Synchronous Speed

When DFAM is operated at synchronous speed, due to the low frequency of the rotor currents, unbalanced thermal heating (unequal distribution of losses among the power devices) is produced in power converters [107]. In addition, it is noted that the junction temperature in power semiconductor devices (IGBT) during low-frequency rotor voltage is higher which results high junction temperature swings [108]. Hence, the large rated DFAMs are not preferred to operate at synchronous speed and it is considered as an insensitive band. However, the research has been continuously undertaken to reduce the dead band around the synchronous speed [109].

VI. Simulation and Experimental Results

In order to demonstrate the operational issues, the DFAM-fed variable speed PSPP is simulated in MATLAB software through Simulink and the structure is executed based on Fig. 12 (in the Appendix) at hydropower simulation laboratory of Water Resources Development and Management Department, IIT Roorkee. A 306-MVA, 0.95 power factor DFAM is considered with five channel back-to-back IGBT-based converters connected in parallel (5 MW each) with a redundant converter of 5 MW rating (see Fig. 4) and simulation is carried out in 3.40 GHz i7 core CPU 8 GB ram computer. The Simulink model is developed considering pump load characteristics. During simulation, the machine is operated at the speed of 1.014 p.u. rpm (Syn. Speed +0.7%) considering load torque of 1.028 p.u. The results obtained during normal operation of DFAM are as follows: stator current—10135 A (rms); stator voltage (P–P)—15 750 V (rms); rotor Current—10 225 A (rms); rotor voltage (P–P)—435 V (rms) and the results of each test (operational issues) are discussed. The machine parameters are listed in the Appendix (Test machine 1).

Experimental setup with available facility in laboratory, shown in Fig. 6, is developed to validate the results obtained from simulation tests. Machine parameters are given in the Appendix (Test machine 2). Vector control of DFAM is achieved through a two level back-to-back IGBT based converter module (PEC16DSM0-45). Grid-side converter (GSC) controls the dc link voltage and rotor-side converter (RSC) controls the speed and reactive power delivery of machine.

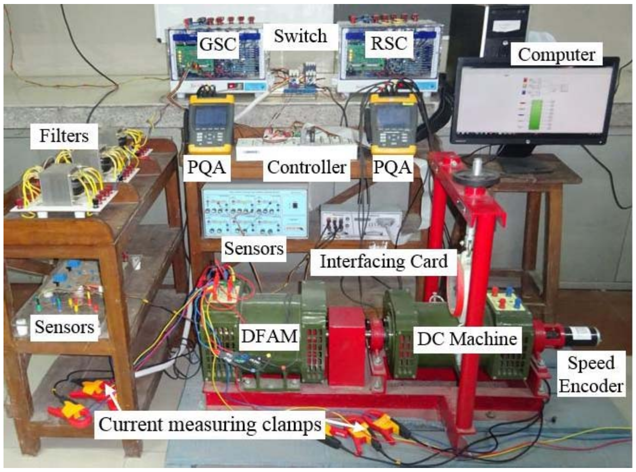

Fig. 6. Experimental setup.

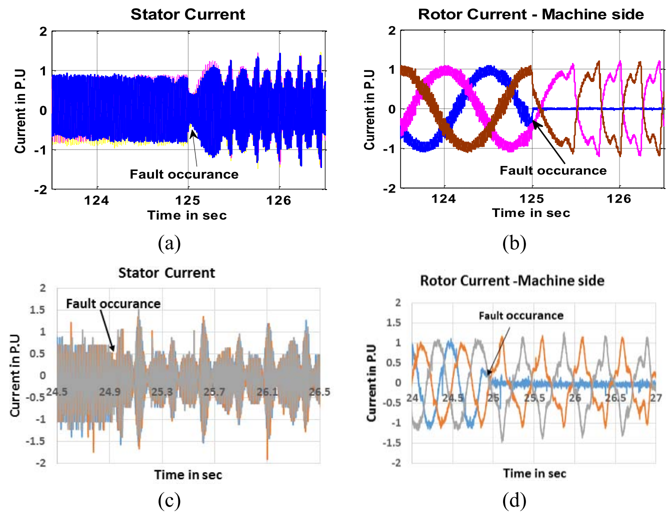

Fig. 7. (a) and (b) Simulation results of dynamic performance of 250-MW DFAM under faults (RSC-single leg power converter fault). (c) and (d) Experimental results of dynamic performance of 2.2-kW DFAM under faults (RSC—single leg power converter fault).

GSC and RSC are controlled by a dSPACE 1104 real time controller (TMS320F240 DSP). SPWM pulses (carrier frequency of 2200 Hz and dead band of 6 μs) generated in MATLAB Simulink are given to converters through the controller. Inbuilt Hall effect current sensors in converter module is used for measuring rotor and stator currents and quadrature encoder pulse (QEP) type encoder (1024 pulses per revolution) is used for speed and position measurement. Current, voltage, and power are measured by Fluke-435 power quality analyzers (both stator and rotor sides) and recorded through dSPACE control desk 3.7.3 automation. The dc link voltage of back-to-back two-level converter is maintained at 325 V and the sample time is 0.001 s. During experimental tests, machine is instructed to operate in supersynchronous pumping mode with the rotating speed of 1.04 p.u. and load torque is considered as 0.7 p.u. In consideration of available facility in the laboratory, few simulation results are validated with the experimental tests conducted in the laboratory and remaining simulation results are validated with experimental results reported in [7] and [110].

A. Test 1: Power Redundancy

A 250-MW with 5×5 MW power converters in rotor circuit is considered, as shown in Fig. 4, for simulation. A single leg open circuit fault in RSC is injected at 125 s and the results are shown in Fig. 7(a). When fault occurs, one of the phase current in rotor goes to zero and the conduction mode is equivalent to the single phase converter with other two healthy legs. The magnitude of currents in healthy legs reaches to 1.15 p.u. [Fig. 7(a)]. Stator phase currents reach to 1.42 p.u. to drive the load.

During experiment, at laboratory, single leg open circuit fault is injected at 25 s and results are shown in Fig. 7(b). Results obtained from the experiment validate the results obtained from simulation. It is noted that both stator and rotor currents exceed their rated values which causes shutdown of hydrogenating unit. On the other hand, if circuit is having power converter redundancy, the faulty converter in rotor circuit shall be replaced with the standby converter for the continuous operation of generating units.

B. Test 2: Effect of Contactor Employed to Provide Power Redundancy

As discussed in Section IV-A, the provision of contactor in series with the power converter provides power redundancy during the converter fault. In order to investigate the effect of this option, a contactor is connected in series with each converter as shown in Fig. 4. The simulation is carried out by introducing a single leg open circuit fault within any one of the main converter [Fig. 7(a)] at 125 s and the fault is detected by the desaturation and circulating current fault detection techniques. The faulty converter is isolated from the system by contactor as well as redundant converter comes to the action for continuous operation of the plant. It is observed that phase voltage in rotor winding reaches to 1.75 p.u., shown in Fig. 8 during isolation of faulty converter. Over voltage in rotor windings leads to deteriorate the life of insulation.

C. Test 3: Detection of DC Component During a Fault

Rotor side short circuit faults (phase–phase and single leg) are injected at 125 s. During faults, high magnitude (about 1.85 p.u.) and very low-frequency ($<$0.5 Hz) rotor phase currents are produced as shown in Fig. 9(a). High magnitude and dynamic variation of frequency in rotor fault currents are challengeable in detection. Further, high dc or extremely low-frequency fault currents are also challengeable in disruption by contactors. Experimental results reported in [7] validate the simulation results obtained.

D. Test 4: Control Redundancy

Closed loop vector control system to facilitate desired dynamic performance of DFAM-fed variable speed PSPP

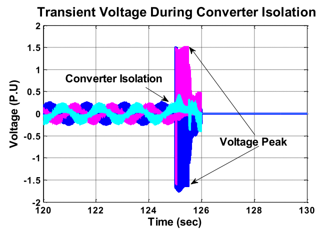

Fig. 8. Response of contactor used isolation and redundant operation of power converter—250 MW DFAM.

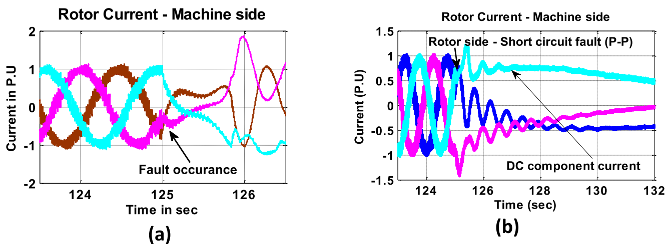

Fig. 9. DC component current. (a) Response of rotor side short-circuit fault (P–P). (b) Response of rotor side—short-circuit fault (IGBT—single leg).

requires encoder, dc link voltage, grid voltage, grid current, stator current, and rotor current sensors. The encoder omission fault is injected in the closed loop control system and observe the performance of the drive (omission fault is modeled by setting the sensor output to zero). The performance measures are set for speed, dc link voltage, current and settling time. The performance bounds are considered as follows: 1) speed variation is ±0.05 p.u. rpm; 2) dc link voltage variation is ±0.1 p.u.; 3) current is acceptable up to 1.2 p.u.; and 4) controller settling time is less than 250 ms.

The encoder fault is injected at 125 s and the results are shown in Fig. 10. During fault, speed controller reads input as zero and increases proportional gain of the controller which increases the speed of machine. Consequently, frequency of rotor current increases, shown in Fig. 10(a), until the speed gets saturated. From the test results, it is summarized as: 1) speed of the machine increases until the q-axis rotor current (Iqr) gets saturated; 2) increase in Idg (direct axis current—grid) to maintain the dc link voltage; and 3) reactive power delivery/consumption during encoder fault is unchanged. The probability of the survival of DFAM under the said fault is analyzed with the performance bounds. Results show that the unit fails to continue its operation under encoder omission faults, hence control redundancy is necessary to increase the continuity of operation of hydrogenating units.

E. Test 5: Deficiency in Protection of Power Converter

Single stage protection (crowbar protection) of the power converter in doubly fed induction machine is continuously disturbed the service of the plant even the fault is not severe. Voltage sag of 0.3 p.u. depth is applied between 125 and 140 s (duration15 s) and results are shown in Fig. 11. Performance bounds are considered as discussed in test 4. Results

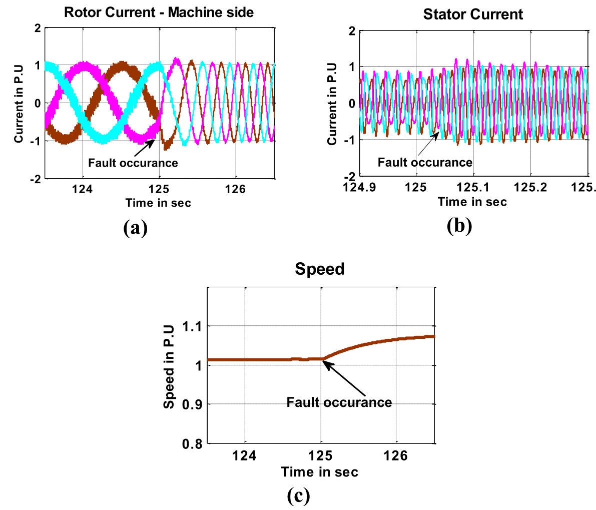

Fig. 10. Response of Encoder fault. (a) Rotor current—machine side. (b) Stator current. (c) Speed.

show (Fig. 11) that the parameter measures are near or slightly above the performance bounds, the crowbar protection is activated for this disturbance and the plant gets shut down. But if we are adjusting the parameter limits with the consideration of modest performance degrades will increase the survival of the plant under this fault. Otherwise, the suitable circuit is required to suppress the rotor current with the considerable limit helps to continuous operation of the plant of the disturbance.

Experimental results reported in [110] validate the simulation results obtained. It was observed that dc link voltage of the back-to-back VSC rises up to 1.3 p.u. and consequently crowbar protection is activated during the grid disturbances (voltage sag).

VII. Future Research Challenges

As reported in [2], [5], [17], and [29], many projects are under construction or at planning stage with the consideration of DFAM-fed variable speed PSPP. Sections V and VI explained various operational issues of these plants with test results. These sections provide some research initiations/directions to cancel out the above said issues. These are considered as the future research challenges and are given as follows.

1) The significant advantages of improved dynamic performance, unity power factor, reduction in THD are the main reasons that multilevel VSCs are applied in variable speed PSPP. However, inventions in power semiconductor devices, modulation schemes, and converter topologies will intensely influence the future growth of power electronics in large rated variable speed PSPP.
2) From the test 2 results presented in Section VI, it was observed that overvoltage occurred in rotor windings during the interruption of contactors. In view of this issue, future research shall be initiated to design a power redundancy system suitable for PSPP without contactors. It may be planned to be removed PWM pulses from faulty converters (for open circuit and other faults except

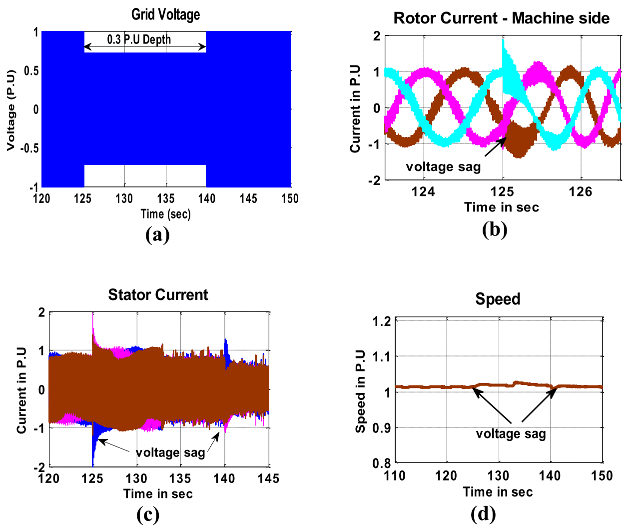

Fig. 11. Response of voltage sag of depth 0.3 p.u. and duration 15 s. (a) Grid voltage. (b) Rotor current—machine side. (c) Stator current. (d) Speed.

TABLE IV
PARAMETERS OF TEST MACHINES

Parameters of Test Machine 1 DFAM (306 MVA, 0.9 - 0.95 P.F, 26 poles, 230.77 rpm, 50 Hz)			
Stator voltage	15750 V	Rotor inductance	0.00507 H
Stator current	11250 A	Stator leakage inductance	0.00038 H
Rotor voltage	3300 V	Rotor leakage inductance	0.00052 H
Rotor current	11600 A	Magnetizing inductance	0.00455 H
Stator resistance	0.00252 Ω	Moment of Inertia	4.6 e^6 kgm^2
Rotor resistance	0.00104Ω	Friction of coefficient	0.006kgm^2/s
Stator inductance	0.00494 H	Sampling Time	0.0001s
Parameters of Test Machine 2 DFAM (2.2 kW, 4 poles, 1460 rpm, 50 Hz)			
Stator voltage	415 V	Rotor inductance	306.82 mH
Stator current	4.7 A	Stator leakage inductance	24.87 mH
Rotor voltage	185 V	Rotor leakage inductance	24.87 mH
Rotor current	7.5 A	Magnetizing inductance	281.96 mH
Stator resistance	3.678 Ω	Moment of Inertia	0.014 kgm^2
Rotor resistance	5.26 Ω	Friction of coefficient	0.03kg m^2/s
Stator inductance	306.82 mH	Sampling Time	0.001s

short circuit in two/more legs) and issue PWM pulses to redundant converters in a short time governed by the master controller.

3) It was observed from test 4, presented in Section VI, that sensor failure or a fault occurred in controller result to stoppage of hydrogenating unit. Hence, an effective control redundancy is highly recommended to increase the continuity of operation of such generating units. V/f scalar or sensor less vector control may be considered as back up control upon the faults occurred in sensors.
4) As discussed in Section V-C and Test 5 shows that the protection deficiency in DFAM drive results to more stoppage of the plant and also leads to instability in the grid. So, it is recommended to add the dc link chopper protection system [dc link chopper circuit has to be installed in every converter module to dissipate the excess energy in the rotor circuit of the machine] in the large rated plant with the crowbar protection system to improve the fault ride-through capability and continuous operation of the plant.

The main theme of dc link chopper protection is to protect the converter and the rotor windings from grid faults and it does not affect crowbar protection based on the severity of the fault, then the plant is in continuous service. (e.g., consider a voltage sag in the grid as 0.1 p.u. and it produces the disturbance in rotor current that increases to about 1.1 p.u., during this time dc link chopper protection is enabled that dissipate the energy via resistance and essentially crowbar circuit should not be enabled). But if the fault is very severe (voltage sag is more than 0.4 p.u. with a considerable time period or short-circuit faults occur in grid) then both (crowbar and dc link chopper circuit) protection circuit will be enabled and the unit gets shut down. A combination of these two protection circuits provides better fault ride-through capability and reduces the stoppages in large rated plant.

Both crowbar and dc link chopper-based protection circuits for DFAM serving in wind power systems are discussed in [112] and [113]. Research is also deliberated on such protection schemes for a mini pumped hydropower plant [114]. Nonetheless, the adaptation of both protection circuits are not yet applied in any commissioned large rated variable speed PSPP.

5) DC chokes, PSTs, interphase reactors, interleaved PWM with discontinuous space-vector modulation techniques and individual control strategies are the practically used methods to mitigate the circulating current. However, zero and negative nonzero sequence circulating current cannot be eliminated by the aforementioned methods, hence, coordinated control of an individual controller is to be implemented to limit such a circulating current component.
6) The design of capacitance and dc link voltage is selected by considering the extra burden that occurs during the grid disturbances (voltage drop, short circuit fault, and frequency drop).

VIII. CONCLUSION

This paper has reviewed the power converter topologies, modulation techniques, and their suitability in DFAM-fed variable speed PSPP. In addition, it is clearly presented the operational issues of the parallel converter in large rated variable speed PSPP with the simulation and experimental results. The importance of converter redundancy is presented with economic benefits, hence, the converter redundancy in parallel converter system is essential for the continuous operation of the plant which increases the reliability and provides more economical benefits. Also, the status of the protection circuit is analyzed and it is to be noted that the plant should have an additional protection circuit for converters with crowbar protection and improves fault ride-through capability. In view of operational issues, it is concluded that the suitable parallel converter scheme should be utilized for the proper power sharing with converter redundancy and the accurate control system is to be implemented for mitigating the circulating current. Furthermore, it is decided that the importance and

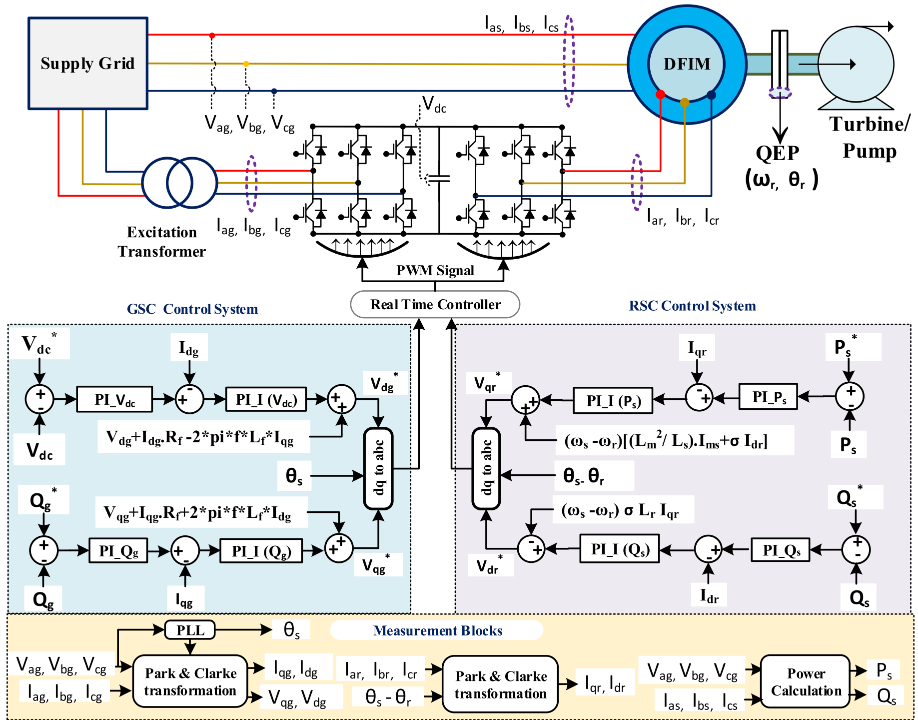

Fig. 12. Control diagram for DFAM serving in variable speed PSPP.

increasing technical requirements of the converter in variable speed PSPP drives will require substantial efforts and research in the future.

Appendix

See Fig. 12 and Table IV.

Acknowledgment

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References

[1] J. P. Deane, B. P. Ó Gallachóir, and E. J. McKeogh, "Techno-economic review of existing and new pumped hydro energy storage plant," *J. Renew. Sustain. Energy Rev.*, vol. 14, no. 4, pp. 1293–1302, May 2010.

[2] M. Swain, "Pumped storage hydropower plant," *Electr. India*, vol. 53, no. 11, pp. 127–136, Nov. 2013.

[3] R. R. Singh, T. R. Chelliah, and P. Agarwal, "Power electronics in hydro electric energy systems—A review," *J. Renew. Sustain. Energy Rev*, vol. 32, pp. 944–959, Apr. 2014.

[4] N. Lefebvre, M. Tabarin, and O. Teller, "A solution to intermittent renewables using pumped hydropower," *Renew. Energy World Mag.*, vol. 18, no. 3, pp. 1–6, May 2015.

[5] T. Kuwabara, A. Shibuya, H. Furuta, E. Kita, and K. Mitsuhashi, "Design and dynamic response characteristics of 400 MW adjustable speed pumped storage unit for Ohkawachi power station," *IEEE Trans. Energy Convers.*, vol. 11, no. 2, pp. 376–384, Jun. 1996.

[6] G. Cavazzini and J. I. Pérez-Díaz, "Technological developments for pumped hydro energy storage," Eur. Energy Res. Alliance, Tech. Rep., May 2014, pp. 1–128.

[7] C. An *et al.*, "Design and testing of a new protection relay for variable speed DFI motor generators," in *Proc. 12th IET Int. Conf. Develop. Power Syst. Protection*, Copenhagen, Denmark, Apr. 2014, pp. 1–6.

[8] (Mar. 2013). *ABB: HVDC Fundamentals Tutorial*. [Online]. Available: http://www.ercot.com/meetings/rpg-crez/keydocs/2007/RPGCREZ20071008/HVDC.pdf

[9] R. Pena, J. C. Clare, and G. M. Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation," *IEE Proc.-Electr. Power Appl.*, vol. 143, no. 3, pp. 231–241, May 1996.

[10] V. Yaramasu, B. Wu, P. C. Sen, S. Kouro, and M. Narimani, "High-power wind energy conversion systems: State-of-the-art and emerging technologies," *Proc. IEEE*, vol. 103, no. 5, pp. 740–788, May 2015.

[11] F. Blaabjerg and K. Ma, "Future on power electronics for wind turbine systems," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 1, no. 3, pp. 139–152, Sep. 2013.

[12] *Technical Standards for Connectivity to the Grid—Hydropower Plant*, Central Electr. Authority India, New Delhi, India, 2007.

[13] F. Barati, R. McMahon, S. Shao, E. Abdi, and H. Oraee, "Generalized vector control for brushless doubly fed machines with nested-loop rotor," *IEEE Trans. Ind. Electron*, vol. 60, no. 6, pp. 2477–2485, Jun. 2013.

[14] S. Basak and C. Chakraborty, "Dual stator winding induction machine: Problems, progress, and future Scope," *IEEE Trans. Ind. Electron*, vol. 62, no. 7, pp. 4641–4652, Jul. 2015.

[15] R. Joseph and L. Umanand, "A brushless wound rotor induction generator for variable speed microhydel plants without ballast load," *IEEE Trans. Sustain. Energy*, vol. 6, no. 1, pp. 20–27, Jan. 2015.

[16] J. I. Pérez-Díaz, M. Chazarra, J. García-González, G. Cavazzini, and A. Stoppato, "Trends and challenges in the operation of pumped-storage hydropower plants," *J. Renew. Sustain. Energy Rev.*, vol. 44, pp. 767–784, Apr. 2015.

[17] J. K. Lung, Y. Lu, W. L. Hung, and W. S. Kao, "Modeling and dynamic simulations of doubly fed adjustable-speed pumped storage units," *IEEE Trans. Energy Convers.*, vol. 22, no. 2, pp. 250–258, Jun. 2007.

[18] I. Erlich and U. Bachmann, "Dynamic behavior of variable speed pump storage units in the German electric power system," in *Proc. 15th Triennial World Congr. Conf.*, Barcelona, Spain, Jul. 2002, pp. 1–6.

[19] M. Nawaz and K. Ilves, "On the comparative assessment of 1.7 kV, 300 A full SiC-MOSFET and Si-IGBT power modules," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, Long Beach, CA, USA, May 2016, pp. 276–282.

[20] S. Linder, "High-power semiconductor devices. Review and comparative assessment," *J. Russian Elect. Eng.*, vol. 78, no. 10, pp. 509–514, Oct. 2007.

[21] M. Pronin, O. Shonin, A. Vorontsov, and G. Gogolev, "A pumped storage power plant with double-fed induction machine and cascaded frequency converter," in *Proc. 14th Eur. Conf. Power Electron Appl.*, Birmingham, U.K., Sep. 2011, pp. 1–9.

[22] X. Yuan, J. Chai, and Y. Li, "A converter-based starting method and speed control of doubly fed induction machine with centrifugal loads," *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1409–1418, Jun. 2011.

[23] A. Karthikeyan, C. Nagamani, A. B. R. Chaudhury, and G. S. Ilango, "Implicit position and speed estimation algorithm without the flux computation for the rotor side control of doubly fed induction motor drive," *IET Electr. Power Appl.*, vol. 6, no. 4, pp. 243–252, Apr. 2012.

[24] J. Lanese, A. Powers, and H. Naeff, "Selection of large variable speed pumps for the Domenigoni valley reservoir project," in *Proc. Int. Conf. Hydropower*, vol. 2. San Francisco, CA, USA, 1995, pp. 1902–1912.

[25] J.-J. Simond, A. Sapin, M. T. Xuan, R. Wetter, and P. Burmeister, "12-pulse LCI synchronous drive for a 20 MW compressor modeling, simulation and measurements," in *Proc. IEEE Conf. Ind. Appl.*, vol. 4. Hong Kong, Oct. 2005, pp. 2302–2308.

[26] S. Mondal and D. Kastha, "Improved direct torque and reactive power control of a matrix-converter-fed grid-connected doubly fed induction generator," *IEEE Trans. Ind. Electron.*, vol. 62, no. 12, pp. 7590–7598, Dec. 2015.

[27] R. Cardenas, R. Pena, G. Tobar, J. Clare, P. Wheeler, and G. Asher, "Stability analysis of a wind energy conversion system based on a doubly fed induction generator fed by a matrix converter," *IEEE Trans. Ind. Electron.*, vol. 56, no. 10, pp. 4194–4206, Oct. 2009.

[28] S. M. A. Cruz and M. Ferreira, "Comparison between back-to-back and matrix converter drives under faulty conditions," in *Proc. IEEE 13th Eur. Conf. Power Electron. Appl.*, Barcelona, Spain, Oct. 2009, pp. 1–10.

[29] T. Friedli, J. Kolar, J. Rodriguez, and P. W. Wheeler, "Comparative evaluation of three-phase AC–AC matrix converter and voltage DC-link back-to-back converter systems," *IEEE Trans. Ind. Electron.*, vol. 59, no. 12, pp. 4487–4510, Dec. 2012.

[30] E. Ghiani, S. Mocci, G. Celli, and F. Pilo, "Increasing the flexible use of hydro pumping storage for maximizing the exploitation of RES in Sardinia," in *Proc. 3rd Renew. Power Generat. Conf. (RPG)*, Sep. 2014, pp. 1–6.

[31] B. Wu, J. Pontt, J. Rodriguez, S. Bernet, and S. Kouro, "Current-source converter and cycloconverter topologies for industrial medium-voltage drives," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2786–2797, Jul. 2008.

[32] A. Bocquel and J. Janning, "Analysis of a 300 MW variable speed drive for pump-storage plant applications," in *Proc. 14th Eur. Conf. Power Electron. Appl.*, Dresden, Germany, Sep. 2010, pp. 56–64.

[33] Y. Pannatier, B. Kawkabani, C. Nicolet, J.-J. Simond, A. Schwery, and P. Allenbach, "Investigation of control strategies for variable-speed pump-turbine units by using a simplified model of the converters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 9, pp. 3039–3049, Sep. 2010.

[34] H. Stemmler and A. Omlin, "Converter controlled fixed frequency variable speed motor/generator," *IEEJ. Trans. Ind. Appl.*, vol. 116, no. 10, pp. 993–1000, Dec. 2008

[35] J. Koutnik, "Frades II—Variable speed pumped storage project and its benefit to the electrical grid," in *Proc. Int. Conf. Renew. Energy*, Orlando, FL, USA, Jan. 2012, pp. 1–7.

[36] A. Sapin, A. Hodder, J. J. Simond, and D. Schafer, "Doubly fed asynchronous machine with 3-level VSI for variable speed pump storage," in *Proc. Int. Conf. Elect. Mach.*, Espoo, Finland, Aug. 2000, pp. 1–6.

[37] E. Schmidt, J. Ertl, A. Preiss, R. Zensch, R. Schürhuber, and J. Hell, "Simulation of steady-state and transient operational behaviour of variable-speed motor-generators of hydro power plants," in *Proc. IEEE Int. Conf. Elect. Mach. Drives*, Niagara Falls, ON, Canada, May 2011, pp. 607–611.

[38] K. Krüger and J. Koutnik, "Dynamic simulation of pump-storage power plants with different variable speed configurations using the Simsen tool," *Int. J. Fluid Mach. Syst.*, vol. 2, no. 4, pp. 334–345, Dec. 2009.

[39] S. Khomfoi and L. Tolbert, *Power Electronics Handbook*, 2nd ed. San Diego, CA, USA: Academic, 2007.

[40] F. Wang and J. Jiang, "A novel static frequency converter based on multilevel cascaded H-bridge used for the startup of synchronous motor in pumped-storage power station," *J. Energy Convers. Manage.*, vol. 52, no. 5, pp. 2085–2091, May 2011.

[41] L. Xu and V. G. Agelidis, "Active capacitor voltage control of flying capacitor multilevel converters," *IEE Proc.-Electr. Power Appl.*, vol. 151, no. 3, pp. 313–320, May 2004.

[42] T. A. Meynard and H. Foch, "Multi-level conversion: High voltage choppers and voltage-source inverters," in *Proc. IEEE Conf. Power Electron. Specialist*, Toledo, Spain, 1992, pp. 21–26.

[43] J. I. Leon, S. Kouro, L. G. Franquelo, J. Rodriguez, and B. Wu, "The essential role and the continuous evolution of modulation techniques for voltage-source inverters in the past, present, and future power electronics," *IEEE Trans. Ind. Electron.*, vol. 63, no. 5, pp. 2688–2701, May 2016.

[44] Y. X. Gao and D. Sutanto, "A method of reducing harmonic contents for SPWM," in *Proc. IEEE Conf. Power Electron. Drive Syst.*, vol. 1. Hong Kong, Jul. 1999, pp. 150–160.

[45] B. Ismail, S. Taib, A. R. M. Saad, M. Isa, and C. M. Hadzer, "Development of a single phase SPWM microcontroller-based inverter," in *Proc. IEEE Int. Power Energy Conf.*, Putra Jaya, Malaysia, Nov. 2006, pp. 423–430.

[46] J. Rodriguez, J.-S. Lai, and F. Z. Peng, "Multilevel inverters: A survey of topologies, controls, and applications," *IEEE Trans. Ind. Electron.*, vol. 49, no. 4, pp. 724–738, Aug. 2002.

[47] D. Krug, S. Bernet, S. S. Fazel, K. Jalili, and M. Malinowski, "Comparison of 2.3-kV medium-voltage multilevel converters for industrial medium-voltage drives," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 2979–2992, Dec. 2007.

[48] R. Saiju, J. Koutnik, and K. Krueger, "Dynamic analysis of start-up strategies of AC excited double fed induction machine for pumped storage power plant," in *Proc. 13th Eur. Conf. Power Electron. Appl.*, Barcelona, Spain, Sep. 2009, pp. 11–18.

[49] Y. Pannatier, B. Kawkabani, C. Nicolet, A. Schwery, and J.-J. Simond, "Optimization of the start-up time of a variable speed pump-turbine unit in pumping mode," in *Proc. 20th Int. Conf. Elect. Mach.*, Marseille, France, Sep. 2012, pp. 2126–2132.

[50] R. S. Kanchan, K. Gopakumar, and R. Kennel, "Synchronised carrier-based SVPWM signal generation scheme for the entire modulation range extending up to six-step mode using the sampled amplitudes of reference phase voltages," *IET Electr. Power Appl.*, vol. 1, no. 3, pp. 407–415, May 2007.

[51] A. R. Beig, G. Narayanan, and V. T. Ranganathan, "Modified SVPWM algorithm for three level VSI with synchronized and symmetrical waveforms," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 486–493, Feb. 2007.

[52] A. K. Gupta and A. M. Khambadkone, "A space vector PWM scheme for multilevel inverters based on two-level space vector PWM," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1631–1639, Oct. 2006.

[53] H. Hu, W. Yao, and Z. Lu, "Design and implementation of three-level space vector PWM IP core for FPGAs," *IEEE Trans. Power Electron.*, vol. 22, no. 6, pp. 2234–2244, Nov. 2007.

[54] T. H. Abdelhamid and K. M. El-Naggar, "Optimal PWM control of a new generalized family of multilevel inverters," *J. Electr. Power Compon. Syst.*, vol. 36, no. 1, pp. 73–92, Jul. 2008.

[55] H. S. Patel and R. G. Hoft, "Generalized techniques of harmonic elimination and voltage control in thyristor inverters: Part I—Harmonic elimination," *IEEE Trans. Ind. Appl.*, vol. IA-9, no. 3, pp. 310–317, May 1973.

[56] D. Ahmadi, K. Zou, C. Li, Y. Huang, and J. Wang, "A universal selective harmonic elimination method for high-power inverters," *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 2743–2752, Aug. 2011.

[57] L. Li, D. Czarkowski, Y. Liu, and P. Pillay, "Multilevel selective harmonic elimination PWM technique in series-connected voltage inverters," *IEEE Trans. Ind. Appl.*, vol. 36, no. 1, pp. 160–170, Feb. 2000.

[58] L. Matakas and E. Masada, "Analysis of the parallel connection of 3-phase VSC converters," in *Proc. Int. Conf. Power Electron.*, Yokohama, Japan, Jul. 1995, pp. 854–859.

[59] J. Hou, Q. Chen, S.-C. Wong, C. K. Tse, and X. Ruan, "Analysis and control of series/series-parallel compensated resonant converter for contactless power transfer," *IEEE J. Emerg. Sel. Topics Power Electron*, vol. 3, no. 1, pp. 124–136, Mar. 2015.

[60] C. K. Sao and P. W. Lehn, "Control and power management of converter fed microgrids," *IEEE Trans. Power Sys.*, vol. 23, no. 3, pp. 1088–1098, Jul. 2008.

[61] B. Ehrman, "Passive current sharing boosts power and reliability," Power Electron. Tech. Mag., Artesyn Technol., Tucson, Ariz, Tech. Rep., pp. 58–59, Jan. 2005

[62] T. B. Lazzarin, G. A. T. Bauer, and I. Barbi, "A control strategy for parallel operation of single-phase voltage source inverters: Analysis, design and experimental results," *IEEE Trans. Ind. Electron.*, vol. 60, no. 6, pp. 2194–2204, Jun. 2013.

[63] R. Majumder, B. Chaudhuri, A. Ghosh, R. Majumder, G. Ledwich, and F. Zare, "Improvement of stability and load sharing in an autonomous microgrid using supplementary droop control loop," *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 796–808, Mar. 2010.

[64] S. Augustine, M. K. Mishra, and N. Lakshminarasamma, "Adaptive droop control strategy for load sharing and circulating current minimization in low-voltage standalone DC microgrid," *IEEE Trans. Sustain. Energy*, vol. 6, no. 1, pp. 132–141, Jan. 2015.

[65] J. C. Vasquez, J. M. Guerrero, A. Luna, P. Rodriguez, and R. Teodorescu, "Adaptive droop control applied to voltage-source inverters operating in grid-connected and islanded modes," *IEEE Trans. Ind. Electron.*, vol. 56, no. 10, pp. 4088–4096, Oct. 2009.

[66] Y. Kanthaphayao, U. Kamnarn, and V. Chunkag, "Redundant operation of a parallel ac to dc converter via a serial communication bus," *J. Power Electron.*, vol. 11, no. 4, pp. 533–541, Jul. 2011.

[67] J.-F. Chen, C.-L. Chu, and Y.-C. Lieu, "Modular parallel three-phase inverter system," in *Proc. IEEE Int. Symp. Ind. Electron.*, vol. 1. Jul. 1995, pp. 237–242.

[68] T.-F. Wu, K. Siri, and C. Q. Lee, "Reliability improvement in parallel connected converter systems," in *Proc. Int. Conf. Ind. Electron., Control Instrum. (IECON)*, vol. 1. Oct. 1991, pp. 429–434

[69] T.-F. Wu, Y.-H. Huang, Y. K. Chen, and Z.-R. Liu, "A 3C strategy for multi-module inverters in parallel operation to achieve an equal current distribution," in *Proc. Conf. Rec. 29th Annu. IEEE Power Electron. Specialists (PESC)*, vol. 1. May 1998, pp. 186–192.

[70] T.-F. Wu, Y.-K. Chen, and Y.-H. Huang, "3C strategy for inverters in parallel operation achieving an equal current distribution," *IEEE Trans. Ind. Electron.*, vol. 47, no. 2, pp. 273–281, Apr. 2000.

[71] X. Sun, Y.-S. Lee, and D. Xu, "Modeling, analysis, and implementation of parallel multi-inverter systems with instantaneous average-current-sharing scheme," *IEEE Trans. Power Electron.*, vol. 18, no. 3, pp. 844–856, May 2003.

[72] W. Jiang and B. Fahimi, "Active current sharing and source management in fuel cell–battery hybrid power system," *IEEE Trans. Ind. Electron.*, vol. 57, no. 2, pp. 752–761, Feb. 2010.

[73] C. T. Pan and Y. H. Liao, "Modeling and coordinate control of circulating currents in parallel three-phase boost rectifiers," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 825–838, Apr. 2007.

[74] B. Chen, Y. Chen, C. Tian, J. Yuan, and X. Yao, "Analysis and suppression of circulating harmonic currents in a modular multilevel converter considering the impact of dead time," *IEEE Trans. Power Electron.*, vol. 30, no. 7, pp. 3542–3552, Jul. 2015.

[75] F. Wang, Y. Wang, Q. Gao, C. Wang, and Y. Liu, "A control strategy for suppressing circulating currents in parallel-connected PMSM drives with individual dc links," *IEEE Trans. Power Electron.*, vol. 31, no. 2, pp. 1680–1691, Feb. 2016.

[76] J. Verboomen, D. Van Hertem, P. H. Schavemaker, W. L. Kling, and R. Belmans, "Phase shifting transformers: Principles and applications," in *Proc. IEEE Int. Conf. Future Power Syst.*, Amsterdam, The Netherlands, Nov. 2005, pp. 1–6.

[77] J. G. Boudrias, "Power factor correction and energy saving with proper transformer, phase shifting techniques and harmonic mitigation," in *Proc. Large Eng. Syst. Conf. Power Eng.*, Halifax, NS, Canada, Jul. 2004, pp. 98–101.

[78] K. Xing, F. C. Lee, D. Borojevic, Z. Ye, and S. Mazumder, "Interleaved PWM with discontinuous space-vector modulation," *IEEE Trans. Power Electron.*, vol. 14, no. 5, pp. 906–917, Sep. 1999.

[79] Z. Ye, D. Boroyevich, J.-Y. Choi, and F. C. Lee, "Control of circulating current in two parallel three-phase boost rectifiers," *IEEE Trans. Power Electron.*, vol. 17, no. 5, pp. 605–609, Sep. 2002.

[80] C. Wen, J. Li, X. Zhu, and H. Xu, "Research on circulation of parallel three-phase converters in MW wind power system," in *Proc. Workshop Power Electron. Intell. Transp. Syst. (PEITS)*, Aug. 2008, pp. 349–354.

[81] C.-T. Pan and Y.-H. Liao, "Modeling and control of circulating currents for parallel three-phase boost rectifiers with different load sharing," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2776–2785, Jul. 2008.

[82] Y. Song and B. Wang, "Survey on reliability of power electronic systems," *IEEE Trans. Power Electron.*, vol. 28, no. 1, pp. 591–604, Jan. 2013.

[83] R. R. Errabelli and P. Mutschler, "Fault-tolerant voltage source inverter for permanent magnet drives," *IEEE Trans. Power Electron.*, vol. 27, no. 2, pp. 500–508, Feb. 2012.

[84] B. Lu and S. K. Sharma, "A literature review of IGBT fault diagnostic and protection methods for power inverters," *IEEE Trans. Ind. Appl.*, vol. 45, no. 5, pp. 1770–1777, Sep. 2009.

[85] H. H. Memon and M. M. Alam, "Reliability, maintainability, availability and failure rate analysis of IGBT triggering system designed for marine environment," in *Proc. IEEE 13th Int. Conf. Appl. Sci. Technol.*, Bhurban, Pakistan, Mar. 2016, pp. 1–5.

[86] P. W. Wheeler *et al.*, "A comparison of the reliability of a matrix converter and a controlled rectifier-inverter," in *Proc. IEEE Eur. Conf. Power Electron. Appl.*, Dresden, Germany, Sep. 2005, pp. 1–7.

[87] M. E. Corporation, "Power module reliability: Products- semiconductors," Power modules, Japan, Tech. Rep. 512, Aug. 2013, pp. 1–13

[88] S. Yang, P. Bryant, A. Mawby, D. Xiang, L. Ran, and P. Tavner, "An industry-based survey of reliability in power electronic converters," *IEEE Trans. Power Electron.*, vol. 25, no. 3, pp. 1441–1451, Nov. 2010.

[89] D. Dufournet and R. W. Alexander, "Transient recovery voltage for high voltage circuit breakers," Alstom, San Antonia, TX, USA, Tech. Rep., 2013, pp. 1–41.

[90] D. L. Swindler, P. Schwartz, P. S. Hamer, and S. R. Lambert, "Transient recovery voltage considerations in the application of medium-voltage circuit breakers," *IEEE Trans. Ind. Appl.*, vol. 33, no. 2, pp. 383–388, Mar. 1997.

[91] *IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers*, IEEE Standard C37.011-2011 (Revision of IEEE Std C37.011-2005), pp. 1–97, Nov. 2011 .

[92] D. Braun and G. Koeppl, "Transient recovery voltages during the switching under out-of-phase conditions," in *Proc. IEEE Intl. Conf. Power Syst. Transients*, New Orleans, LA, USA, Sep. 2003, pp. 1–5.

[93] D. Dufournet, "Transient recovery voltages for high-voltage circuit breakers—Part 1," Alstom Grid, San Antnoia, TX, USA, Tech. Rep., Sep. 2013, pp. 1–186.

[94] K. Kadriu, A. Gashi, I. Gashi, A. Hamiti, and G. Kabashi, "Influence of dc component during inadvertent operation of the high voltage generator circuit breaker during mis-synchronization," *J. Energy Power Eng.*, vol. 5, no. 3, pp. 225–235, Mar. 2013.

[95] *IEEE Standard for AC High-Voltage Generator Circuit—Breaker Rated on a Symmetrical Current Basis*, Revision of IEEE Standard C37.013-1993, May 2005.

[96] J. Machowski, J. W. Bialek, and J. R. Bumby, *Power System Dynamics and Stability*, 2nd ed. Hoboken, NJ, USA: Wiley, 2008.

[97] N. Ahmed *et al.*, "HVDC super grids with modular multilevel converters—The power transmission backbone of the future," in *Proc. Int. Conf. Syst., Signals Devices*, Chemnitz, Germany, Mar. 2012, pp. 1–7.

[98] J. Candelaria and J. D. Park, "VSC-HVDC system protection: A review of current methods," in *Proc. IEEE/PES Power Syst. Conf. Expo. (PSCE)*, Mar. 2011, pp. 1–7.

[99] C. M. Franck, "HVDC circuit breakers: A review identifying future research needs," *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 998–1007, Apr. 2011.

[100] O. Noureldeen, "Behavior of DFIG wind turbines with crowbar protection under short circuit," *Int. J. Elect. Comput. Sci.*, vol. 12, no. 3, pp. 32–37, Jun. 2012.

[101] J.-H. Liu, C.-C. Chu, and Y.-Z. Lin, "Applications of nonlinear control for fault ride-through enhancement of doubly fed induction generators," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 4, pp. 749–763, Dec. 2014.

[102] G. Pannell, D. J. Atkinson, and B. Zahawi, "Minimum-threshold crowbar for a fault-ride-through grid-code-compliant DFIG wind turbine," *IEEE Trans. Energy Convers.*, vol. 25, no. 3, pp. 750–759, Sep. 2010.

[103] M. M. Baggu, B. H. Chowdhury, and J. W. Kimball, "Comparison of advanced control techniques for grid side converter of doubly-fed induction generator back-to-back converters to improve power quality performance during unbalanced voltage dips," *IEEE J. Emerg. Sel. Topics Power Electron*, vol. 3, no. 2, pp. 516–524, Jun. 2015.

[104] S. R. Kalantarian and H. Heydari, "A new crowbar protection method for improvement in performance of doubly fed induction generator under fault conditions," in *Proc. 10th Int. Conf. Environ. Elect. Eng. (EEEIC)*, May 2011, pp. 1–4.

[105] R. Maheshwari, G. Gohil, L. Bede, and S. Munk-Nielsen, "Analysis and modelling of circulating current in two parallel-connected inverters," *IET Power Electron.*, vol. 8, no. 7, pp. 1273–1283, Jul. 2015.

[106] M. H. Ravanji, N. A. Ashtiani, M. Parniani, and H. Mokhtari, "Modeling and control of zero-sequence circulating current in parallel converters with space vector modulation," *IEEE J. Emerg. Sel. Topics Power Electron*, vol. 5, no. 1, pp. 363–377, Mar. 2017.

[107] M. Bruns, B. Rabelo, and W. Hofmann, "Investigation of doubly-fed induction generator drives behaviour at synchronous operating point in wind turbines," in *Proc. 13th Eur. Conf. Power Electron. Appl.*, Barcelona, Spain, Sep. 2009, pp. 1–10.

[108] L. Wei, J. McGuire, and R. A. Lukaszewski, "Analysis of PWM frequency control to improve the lifetime of PWM inverter," *IEEE Trans. Ind. Appl.*, vol. 47, no. 2, pp. 922–929, Mar./Apr. 2011.

[109] M. Z. Sujod, I. Erlich, and S. Engelhardt, "Improving the reactive power capability of the DFIG-based wind turbine during operation around the synchronous speed," *IEEE Trans. Energy Convers.*, vol. 28, no. 3, pp. 736–745, Sep. 2013.

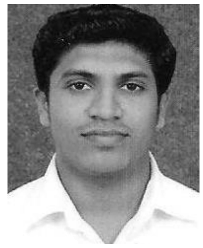
[110] R. Zhu, Z. Chen, Y. Tang, F. Deng, and X. Wu, "Dual-loop control strategy for DFIG-based wind turbines under grid voltage disturbances," *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 2239–2253, Mar. 2016.

[111] S. Hu, X. Lin, Y. Kang, and X. Zou, "An improved low-voltage ride-through control strategy of doubly fed induction generator during grid faults," *IEEE Trans. Power Electron.*, vol. 26, no. 12, pp. 3653–3665, Dec. 2011.

[112] 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.

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

[114] 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," *J. Renew. Energy*, vol. 95, pp. 248–262, Sep. 2016.



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