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Power electronics in hydro electric energy systems – A review

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A B S T R A C T

Hydropower is a major energy source among the renewable energy sources. According to “BP Statistical Review of World Energy, June 2013”, 16.34 percentage of global power generation acquire from hydropower. To attain efficient generation in hydro plant, extensive design with the up to date technology is mandatory. To make the generation more effective various technologies are adopted, among these the very effective one is power electronics (PE) technology. The paper has reviewed the challenges in how PE technology fits in as the solution for various hydroelectric energy systems (HEES). The PE technology is adapted efficiently in various parts of HEES like, grid integration, machine control, switching (pumping mode to generating mode and vice versa), power control, voltage and frequency control, power factor correction, etc., The advancement of PE technology diminishes the cost and space of the plant and enhances the power handling capability. The paper emergence the outstanding features of power electronics in various aspects that will extensively contribute to the development of HEES around the world. In addition, PE contribution satisfies the need of reliability, dynamic response, efficiency, protection, etc., in HEES.

Contents

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1. Introduction

According to the law of energy conservation, the hydroelectric energy systems are extracting electricity from water. Globally, 3673.1 Terawatt-hours of energy are consumed from hydropower in various countries as shown in Fig. 1. These hydroelectric energy systems are classified according to the accessibility of sources. The traditional hydroelectric plants are capable to produce power up to few GW. Small hydro plants are also available without dam or water storage. According to the plant rating, the small hydro plants are further classified into mini (rated up to 1000 kW), micro (rated up to 100 kW) and Pico (rated up to 5 kW). Pumped storage plant stores electrical energy in the form of potential energy by raising the water to the highest level and utilizes during demand period. This generated power is utilized by the consumers directly or once after synchronizing with the grid, which depends upon their location and rating. In the above process, the voltage and frequency should maintain constant and it can be achieved by controlling the generating machines through PE converters in various aspects like excitation control, dump load control, etc., In pumped storage plants, same machine is operated for both pumping and generation at variable speed to provide more efficiency. This effective operation of the machine can attain through PE converter adapted with different control technique. Hydroelectric generation enabled with the advanced power electronics and proper control strategies possess superior performance in their technical characteristics like voltage and frequency regulation, active and reactive power control, short circuit control, fault ride through, etc., [1]. Therefore, above all generation, conversion and transmission controls would fulfill only with the help of PE technology.

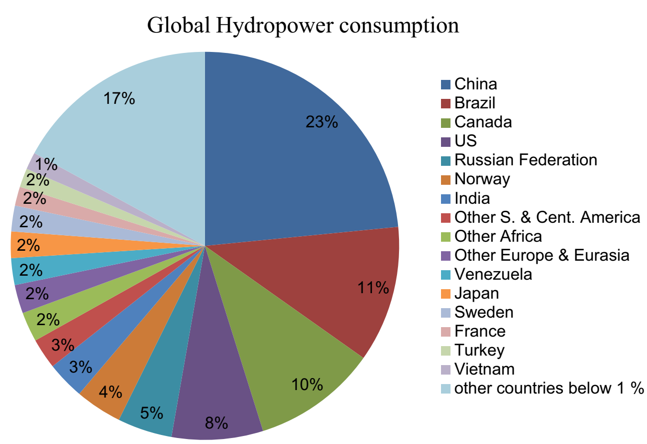

Fig. 1. Global hydropower consumption.
Source: BP Statistical Review of World Energy, June 2013.

The paper depicts the various aspects of power electronics technology in hydroelectric energy system as in Fig. 2. In **section 2** the PE in grid integration, in **section 3** the PE binds with machine control, in **section 4** PE for variable speed operation in both generation and pumping mode of operation, in **section 5** the PE in voltage and frequency control and in **section 6** future trends are described in detail. Finally, the paper concludes in **section 7**.

2. Grid Integration

The interconnection of two or more generating sources in the transmission network is known as grid integration. This balances the supply and demand at all the time and it should be executed

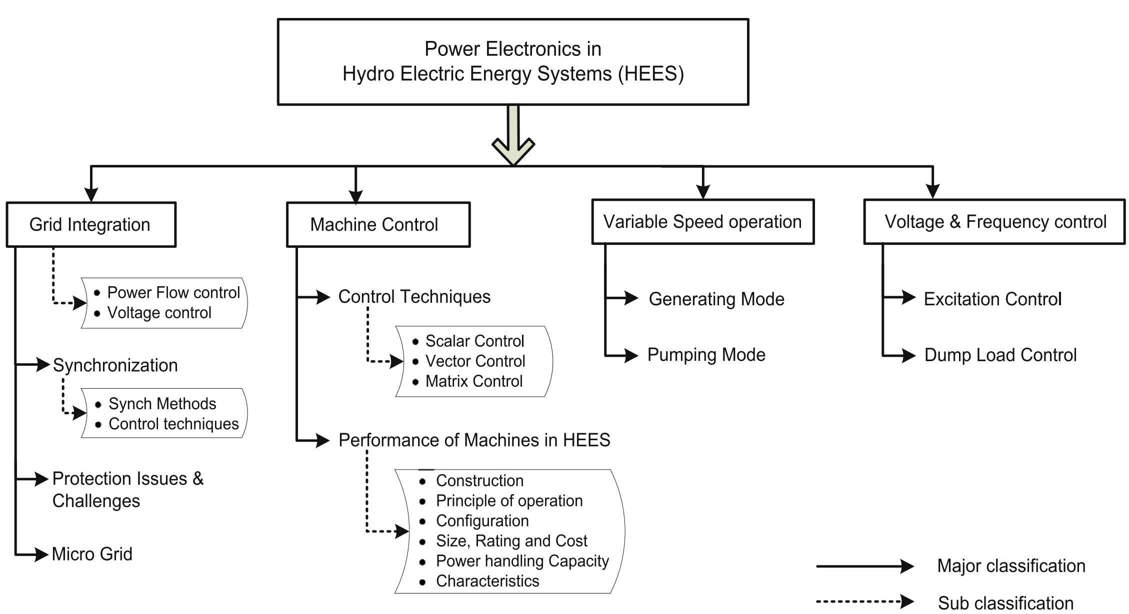

Fig. 2. Perception of the paper.

by the appropriate standards and requirements [2–8]. The sources of renewable energy system (RES) connected to the network may provide continuous or discontinuous supply to the grid. To increase the reliability and stability of the system under both steady state and transient period, a flexible power conditioner is required [9]. The PE topology adopts for these requirements due to its inherent fast switching capability, bi-directional power flow control [10], optimal energy transformation [11] and real time control characteristics of electrical quantities [12–14]. The control architecture of power electronic converters remains consistent and the processing ability of such devices can be improved [15]. The strategies of effective integration of variable renewable energy among different countries are surveyed and cited in [16–19]. The PE requirements in various aspects of grid integration are discussed in detail.

2.1. Synchronization

Synchronization is mandatory during the integration of generating units to the grid. Energy transfer and power flow between the main AC and the grid connected converters are mainly depends on the relative phase angle (φ). Moreover, the grid synchronization must account for the following features like, frequency adaptation, phase-angle adoption, distortion and noise rejection, unbalance robustness, dynamic/convergence time, structural simplicity, computational burden and accuracy [20]. The various methods of grid synchronization are tabularized in the Table 1 and are analyzed in [21–32]. Ref [31, 33–37] compared the relative features of control techniques used for grid synchronization. Depending upon the generation capacity of renewable energy source from a few kilowatts to several megawatts, the sources can be integrated in the distribution level or in transmission level [38–40]. During such integration the PE converters acts as an intermediate device to provide, better reliability, high efficiency, cost effective and more energy harvesting [41–43]. Finally, advanced power electronics greatly empower the renewable energy system through considering the issues like energy efficiency, starting transients and power quality, justified in [44–48].

2.2. Protection issues and challenges

During grid integration the issues like low voltage [49], unbalance voltage [50], voltage sags, change of short circuit level, reverse power flow [51], lack of sustained fault current and islanding during interconnection may occur [52,53]. Power electronics circuits help to overcome these issues. An inverter is used to continue the islanding operation during the removal of grid on purposely or unintentionally. Since, unintentional islanding creates instability to the network like flickering, voltage and frequency unbalance, harmonics occurrence, equipment damage, electric shock, etc., [54]. To detect and protect the unintentional islanding certain methods like active method, passive method, frequency based passive methods and telecommunication based methods are used with the power electronics circuit [49,55]. Also, anti-islanding protection works with the help of PE circuits to keep off unintentional islanding [56,57]. Thus using power electronics, the circuit protection can be improved during intentional and unintentional islanding operation.

2.3. Microgrid

A microgrid is an electrical system that admits multiple loads, distributed energy sources and energy storage that can be operated in parallel with centralized grid. The grid-connected mode and island mode are the two modes of microgrid with energy management and voltage-frequency control objectives respectively [58]. Renewable energy systems based distributed generation could interface to the grid through controllable PE converters to meet the customers and utility demands [59,60]. These converters are classified into grid-feeding converter, grid-supporting converter and grid-forming converters [61]. Power converters with flexible control in the microgrid fulfills the system requirement specifically in reliability, power quality, system efficiency, etc., Together, microgrid on a distributed generation system with power controllers can provide subsidiary services to the main power system particularly in switching operation (grid connection system to islanding mode and vice versa) [58,62]. The succeeding investigation of microgrid increases the promotion of distributed renewable energy resources that reduces carbon emission, increases economic benefits and assures safety [63]. The main challenges of renewable energy grid integration are non-controllable variables, partial unpredictability on the variable source and location dependency sustained on water resources [64,65]. To meet these challenges, an improved power control like active and reactive power droop control, voltage reference compensation, constant power output mode control, phase adjustment mode control can be employed

Table 1
Methods of grid synchronization with various control techniques.

Sl.No	*Methods of synchronization & Control Techniques*	*Application*	*Year [Ref.No]*
1	*Neural Network estimation algorithm*	*Estimation of harmonic components*	*1996* [21]
2	*ANN based non-linear least squares parameter estimation techniques*	*Real-time frequency and harmonic evaluation*	*1999* [22]
3	*SRF-PLL**	*Phase tracking system for three phase grid*	*2000* [23]
4	*DSP based DFT*	*Error estimation and correction scheme for the highly unbalanced condition.*	*2002* [24]
5	*EPLL**	*Provide a high degree of immunity and insensitivity to noise*	*2004* [25], *2011* [20]
6	*DSP based PLL technique*	*Grid failure detection*	*2004* [26]
7	*DFT based Compensation algorithm*	*Harmonics filtration*	*2005* [27]
8	*Dual second order generalized Integrator frequency locked loop**	*Provide stability during transient periods*	*2006* [28]
9	*Dual second order generalized Integrator PLL**	*Positive-sequence voltage detection of power converters under faulty grid conditions*	*2006* [29]
10	*Decoupled Doubled SRF-PLL**	*Detection of positive-sequence component under unbalanced and distorted conditions*	*2007* [30]
11	*Kalman techniques*	*Harmonics filtration*	*2007* [31]
12	*Droop based power sharing control*	*Regulate the phase angle and voltage magnitude*	*2011* [32]

In the Above table: ** denotes synchronization methods*
ANN: Artificial neural network
EPLL: Enhanced phase locked loop
SRFPLL: Synchronous reference frame phase locked loop
DSP: Digital signal processing
DFT: Discrete Fourier transform

[58–68] and the systematic investigation towards increasing the performance are cited in [69].

3. Machine control

In HEES, power electronic control technology serves the machines to run effectively. Initially in hydroelectric generating stations, induction machines are hardly preferred than synchronous machines due to its unsatisfactory performance [70,71]. Recently, PE cascaded converter is employed between the slip-ring terminals of wound-rotor induction machine and the utility grid to control the rotor power [72]. This modified induction machine is known as doubly fed induction machine (DFIM) in which the rotor power control gives better performance characteristics as well as reduce the rating of power converters. But, controlling the DFIM is more complex than controlling the standard induction machine. Here, contribution of flexible power controllers makes the machine control easier and gives better performance to DFIM. The recent growth of PE converters has reincarnated the doubly fed induction machine by replacing cycloconverter with 3-level VSI cascade back-to-back converter [73–75]. The DFIM with PWM back-to-back converter are preferred in hydroelectric power plants to interface electrical utility at variable speed operation which decreases the mechanical stress and acoustic noise thereby improves the power quality [76–78]. Overall, power electronics converters replace the mechanical controls to provide dynamic response and fast recovery during grid failure. Therefore, reliability and efficiency of the PE converters and controllers produces a beneficial impact on the total system performance.

3.1. Control techniques

The PE converters are supervised by different control techniques. The controllers are mandatory to control the machine parameters in order to operate the machine as desired. Presently, various researchers extensively analyze and designing several types of controllers discussed in [79–85] and are tabularized in Table 2. From the literature available, numerous solutions are based on the enforcement of advanced power electronics functionalities in the existing rotor or grid side converters [76]. Among the various control techniques, few familiar controllers have discussed in the next sections.

3.1.1. Scalar control

Scalar control is based on varying two parameters simultaneously. It is a steady state direct control involves controlling the magnitude of voltage and frequency of the induction motor and used as V/Hz constant. The wide range of smooth speed with maximum torque remains unchanged and obtained through proper tuning of voltage and frequency [77,104].

3.1.2. Vector control

It is a dynamic indirect control mainly used in a synchronous and induction machines for attaining high performance. The analysis of vector control is based on the vector representation

Table 2
Various control techniques used for hydro generators.

Sl.No	Control Techniques	Machine type	Type of Power Electronic Converter	Application	Year [Ref. No]
1	INTEL 8086 microprocessor based control	DOIG	Single quadrant converter	Variable speed constant output	1987 [86]
2	Signal processor based direct self-control	SFIM	Voltage source inverter	Speed control	1992 [87]
3	A novel PWM control strategy based on voltage state vectors	SFIM	Two level inverter	Speed control	1993 [84]
4	Motorola DSP56001 based FOC and FLC	DFIM	Dual PWM converter	Speed control	1995 [88]
5	Adaptive maximum power point tracking strategy	DFIG	Back-to-back three phase power converter	Improve the overall efficiency	1995 [89]
6	Sliding mode linearized control	Induction machine	PWM inverter	Speed control	1996 [90]
7	Optimal control strategy	DFIG	Back-to-back three phase power converter	High power efficiency	2001 [91]
8	Non classic control algorithm	DOIG	IGBT based voltage source converter	Speed control	2002 [92]
9	PI with passivity-based control (PCB)	SFIM	Inverter with battery bank	Speed regulation & energy balance	2003 [93], 2003 [94]
10	IDA-PCB techniques	DFIM	Power converter	Power flow control	2004 [95]
11	FMAC scheme	DFIG	Back-to-back variable frequency PWM converter	Power stabilization	2005 [96]
12	Synthesis method with inversion principle	Cascaded DFIG	Back-to-back three phase power converter	Voltage control	2005 [97]
13	Coordination control	DFIG	Frequency-voltage regulation and maintain the flux level	Power control	2006 [98]
14	FOC based power distribution law	DFIM	PWM voltage source inverters	Speed control with reduced converter ratings	2006 [99]
15	PID based decentralized non-linear control	DFIG	Back-to-back three phase power converter	Improve transient stability	2008 [100]
16	PFNN based FOC	DFIG	Three phase current controlled voltage source inverter	Voltage and frequency stability during grid failure	2011 [101]
17	PSO	DFIG	Back-to-back PWM converter	Stability of grid (Sensitivity analysis of the grid)	2012 [102] 2013 [103]
18	IFOC with FLC	DFIG	Back-to-back three phase power converter	Power flow balance	2002 [85]

In the Above table:
FOC: Field oriented control
FLC: Fuzzy logic control
FMAC: Flexible mandatory access control
PFNN: Probabilistic fuzzy neural network
IFOC: Indirect flux oriented control
PSO: Particle swarm optimization
SFIG: Singly fed induction generator
DFIG: Doubly fed induction generator
DFIM: Doubly fed induction machine
DOIG: Doubly output induction generator
IDA-PCB: Interconnection and damping assignment passivity-based control

of current, voltage and magnetic flux. This decoupled control of torque and flux component is based on the d-q synchronous reference frame [70,105]. The vector control system ensures independent control on DC link voltage, wide range operation and optimal speed tracking to attain maximum energy [106]. The various vector control techniques adapted for several applications [85,107–117] are manifestly tabulated in Table 3. The vector control is used to maintain the stator frequency constant under variable speed operation. The active and reactive power is controlled individually by various vector control techniques presented in [118–128] and are tabularized in Table 4. During grid fault, the non-linear control algorithm with direct decoupling helps to improve the ride through a turbine [129]. Also, the steady state and dynamic response of electric machines could be improved by

Table 3
Vector based control of hydro generators.

Sl.No	Control Techniques	Machine Type	Types of Power Electronics Converter	Application	Year [Ref No]
1	Stator flux oriented vector control	DFIG	Back to back PWM voltage source converter	Optimal speed tracking for obtaining maximum energy	1996 [108]
2	Decoupled control of active and reactive power	DFIG	Back-to-back three phase power converter	Torque and power factor control	1997 [109]
3	Indirect vector scheme with front end converter control strategy	DFIM	Back-to-back PWM converters	Speed control and voltage regulation	2002 [110]
4	Decouple stator current and rotor current control	DFIG	Current controlled PWM Inverter	Voltage and frequency control	2002 [111]
5	Stator flux oriented Vector control	PMSM	Back-to-back PWM converters	Speed control and voltage regulation	2003 [112]
6	Feedback control loop with feed forward compensation	DFIM	Voltage fed PWM inverter	Independent active and reactive power control in transient states	2003 [113]
7	PI with the stator flux oriented vector control	DFIG	Three phase PWM converter with DSP TMS320F241	Reduction of flux oscillation	2005 [114]
8	Stator flux oriented	DFIG	Back-to-back three phase power converter	Active and reactive power control	2006 [107]
9	Quasi-steady-state rotor EMF-oriented vector control	DFIG	Four quadrant converter	Improve efficiency and reliability with reduced cost	2006 [115]
10	Stator flux oriented vector control	DFIG	IGBT based back-to-back PWM converters	Simultaneous active and reactive power control	2013 [116]
11	Indirect flux oriented control	DFIG	Four quadrant converter with resistive bank	Power flow balance	2000 [117]

In the Above table:
PMSM: Permanent magnet synchronous machine
DFIG: Doubly fed induction generator

Table 4
Active and reactive power control of hydro generators.

Sl. No	Control Techniques	Machine Type	Types of Power Electronics Converter	Application	Year [Ref. No]
1	Decoupled power controller	DFIG	Cycloconverter	Active and reactive power control	1991 [126]
2	Decoupled controller based position sensor less scheme	DFIM	Bidirectional power flow converter	Torque and reactive power control	1995 [120]
3	Decoupled power controller	DFIG	Single quadrant diode bridge with controlled converter	Robust torque tracking and reactive-power regulation	1998 [119]
4	Indirect control	DFIG	Single quadrant diode bridge with controlled converter	Maximum active power generation	1999 [125]
5	Decoupled power controller	DFIG	IGBT based 6-pulse back to back converter	Optimal active and reactive power control	2001 [121]
6	Vector control	DFIG	Bidirectional power flow converter	Reactive power control	2001 [122]
7	Stator flux oriented control	DFIG	Single quadrant diode bridge with controlled converter	Reactive power control and torque pulsation compensation	2003 [124]
8	Decoupled power controller	DFIG	Four quadrant ac-dc-ac power converter	Active and reactive powers control according to the imposed power limitations	2005 [118]
9	Hopf bifurcation phenomena based vector-controlled	DFIG	Bidirectional power flow converter	Active and reactive power control	2006 [128]
10	Direct power control strategy	DFIG	Back-to-back PWM converter	Active and reactive power control	2007 [142]
11	Vector based direct control	DFIG	Single quadrant diode bridge with controlled converter	Direct active and reactive power control	2008 [127]
12	Vector control based HPSOWM algorithm	DFIG	Bidirectional power flow converter	Reactive power control	2010 [123]

In the Above table:
DFIG: Doubly fed induction generator
DFIM: Doubly fed induction machine
HPSOWM: Hybrid particle swarm optimization with wavelet mutation

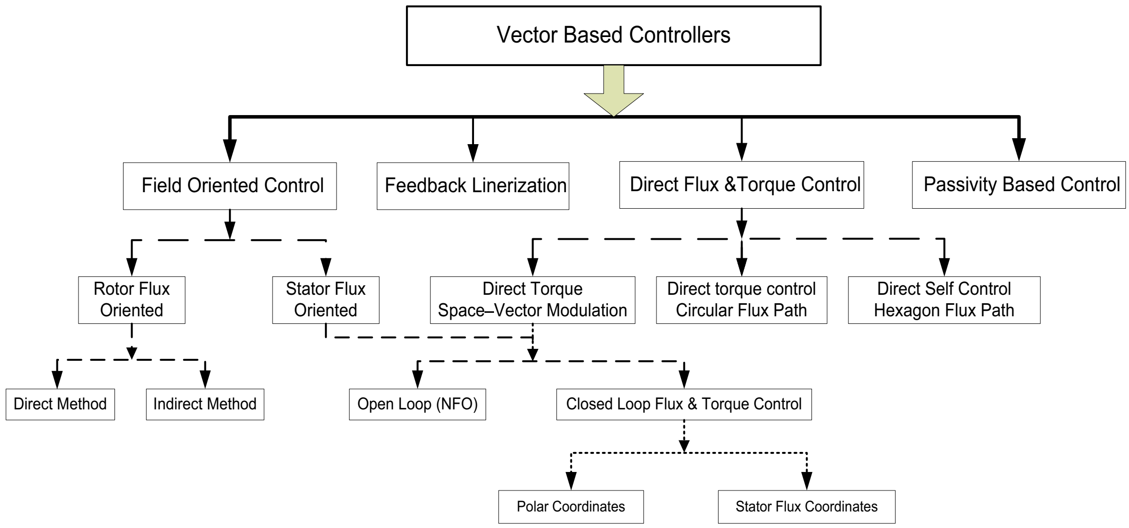

Fig. 3. Depiction of vector based controllers.

using the controllers like fuzzy logic controller, probabilistic neural network controller (PNN), etc., [101,130]. The classification of vector controller is depicted in Fig. 3.

3.1.3. Matrix controller

Matrix converter controllers are inherently bidirectional and are highly preferred to overcome the limitation of conventional two stage power converters with large size, more weight, less reliability, poor line factor, and harmonic distortion, [131,132]. The matrix converter can attain pumping and generating operation effectively without any bulky and costly energy storage components. Moreover, the control strategy is simpler than two-stage power converter, within the same algorithm both the input current and output voltages are modulated [133–136].

Other controllers such as sliding mode control reduces torque oscillation and provides optimum efficiency [137,138]. Also, the wound-rotor induction machine can control by two-cascaded loop (rotor currents controlled by one inner loop and the stator flux controlled by other external loop) with a PI controller [139]. Together with, an additional feed forward compensator can be used to control nonlinear terms [140]. Using back-to-back converter the power flow direction and voltage magnitude between the supply and rotor can be controlled through switching pulses [141].

3.2. Performances of two different machines used in HEES

Vice-versa conversions of electrical energy into mechanical energy are the principles of electrical machines. Commonly hydroelectric energy system (HEES) focuses on synchronous machines due to its constant output, but the recent development of DFIM with flexible power conditioner provides full system control with less power rating [143]. Moreover, DFIM advance in many features like rating, stability, response, smoothening, etc., On account of these features the DFIM received more attention by HEES [80,143,144]. Presently, there is a neck-to-neck race between the synchronous machine and DFIMs, the comparison of both machines are discussed by considering the whole drive train into account [145,146].

3.2.1. Construction

The synchronous machine is a doubly fed machine that consist of a stator with three phase AC winding, R, Y and B are distributed

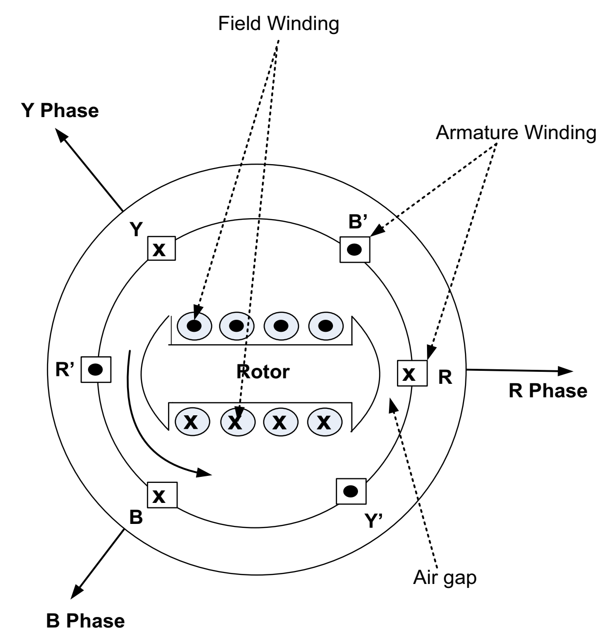

Fig. 4. Schematic representation of salient pole type synchronous machine.

120° apart in space, shown in Fig. 4. This stator winding either exports AC power (synchronous generator) or imports AC power (synchronous motor) and the rotor always energized by the DC supply. Depending upon their construction, the synchronous machines are of two types salient pole and cylindrical pole. The salient pole type is a slow speed machine, mainly employed in HEES. The cylindrical pole type is a high-speed machine that used in high-speed application [147].

The doubly fed induction machine consists of a stator with three-phase AC winding, Rs, Ys and Bs, distributed 120° apart in space, shown in Fig. 5. This winding either exports AC power (generation) or imports AC power (motoring). The rotor of doubly fed induction machine is energized by AC supply, which contains a three-phase distributed winding with the same number of poles as the stator and displaced by angle θ. This winding is usually star connected with the ends of the winding brought out to three slip rings, enabling external circuits to rotor for control purpose [147].

3.2.2. Principle of operation

The synchronous motor works under the principle of electromagnetic attraction, when a three-phase supply is fed to the armature, a rotating magnetic field is produced in armature and it runs at certain speeds. Likewise, when a field winding is excited by the DC supply it becomes an electromagnet and produce field flux. Poles of this electromagnet are magnetically locked with the opposite poles of rotating magnetic field. Together with the rotating magnetic field, the armature will rotate at a speed known as synchronous speed. Similarly, the synchronous generator works under the principle of electromagnetic induction, when the excited field poles rotated, the field flux cuts the armature winding which displaced by 120° henceforth the three-phase AC power will produce at the output [147].

The doubly fed induction machine works under the principle of electromagnetic induction, when the three-phase supply is fed to the stator and rotor at different frequencies, two rotating magnetic fields will be produced. These rotating magnetic fields have different speeds. The interactions of both the field produce the mechanical force. Similarly in DFIG, when the excited rotor rotates, the rotor flux cuts the stator winding which displaced by 120° henceforth the three-phase AC power will produce at the output [147].

3.2.3. Configuration

Generally, the grid allows only little angular offsets and demands a fixed rotation speed of the generator's rotor. Any fluctuations produced by the turbine translate directly into torque variations of the generator that cause the power surges into the grid. In order to solve this fluctuation, many advanced PE elements are increasingly developed. Also, this lets matching of rotation speed and variable speed, contributing to increase efficiency and provides greater annual electricity yields. In addition, power converters could design to produce or absorb the reactive power in order to run the generators at variable speed, as well as to provide a smooth start for running the turbine mildly up to the rated speed. These are the importance of connecting the power electronics topologies in between synchronous generator and electric grid [148].

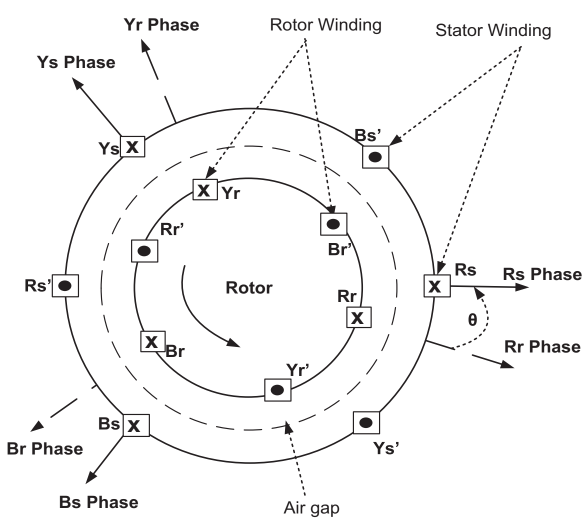

Fig. 5. Schematic representation of doubly fed induction machine.

The main elements of the synchronous machine strategy are as shown in Fig. 6, the generator supplies power to converter known as a frequency converter because its central function is to decouple the turbine's rotation speed from the grid frequency. This is achieved by rectifying the generator's AC output into DC with a stator side converter (SSC), and again inverted back into AC using grid side converter (GSC). As the generator's total power passes through the converters, this strategy is known as full rated or full-scale power conversion. Using this configuration, continuous power can be extracted under variable head, torque surges and switching transients can be reduced [148].

The main elements of the DFIM strategy are as shown in Fig. 7, the bidirectional converters namely rotor side converter (RSC) and grid side converter (GSC) are placed in between the rotor and grid respectively. The speed and torque can be controlled through RSC and voltage in the DC link can be controlled by GSC. Both the converters can control independently through dq-axis components and there is considerable flexibility during the allocation of roles in the units. Also, in DFIM using the power converter may admit the facilities like smooth start, smooth power flow, power factor correction, voltage control, torque control and protection of the turbine from stress [148]. The comparison of synchronous machine and doubly fed induction machine in hydro electric energy system are tabulated in Table. 5.

4. Variable speed operation

In HEES, the variable speed operation is closely related to turbine and electrical machines. The fixed speed turbine in varying head hydro power plant creates instability to the system output. This instability problem can be rectified by replacing the fixed speed turbine with the variable speed turbine. The variable speed turbine in the varying head reservoir can provide the benefits like better efficiency, continuous operation, cavity or draft tube oscillation avoidance and reduce the need of the flooded area.

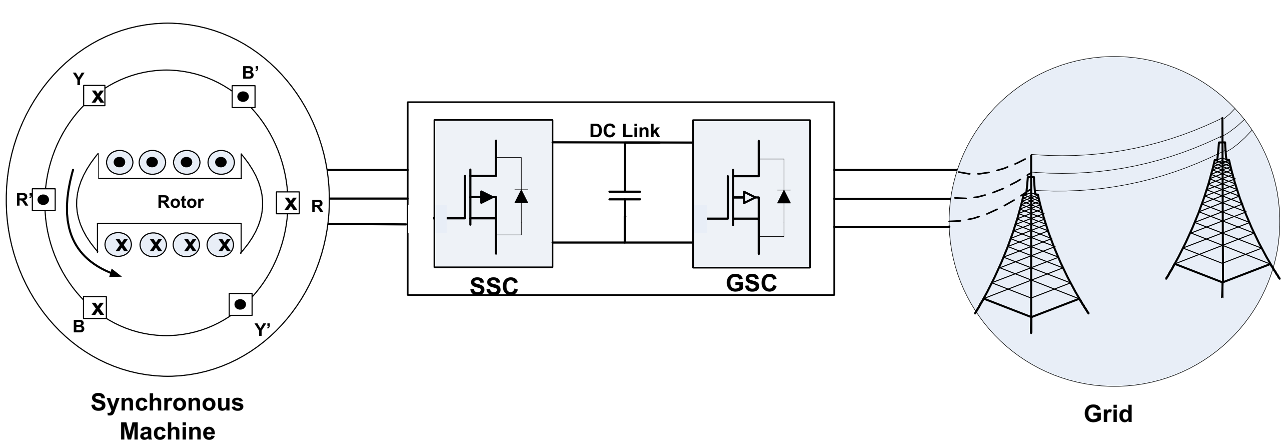

Fig. 6. Configuration of power converters in synchronous machine.

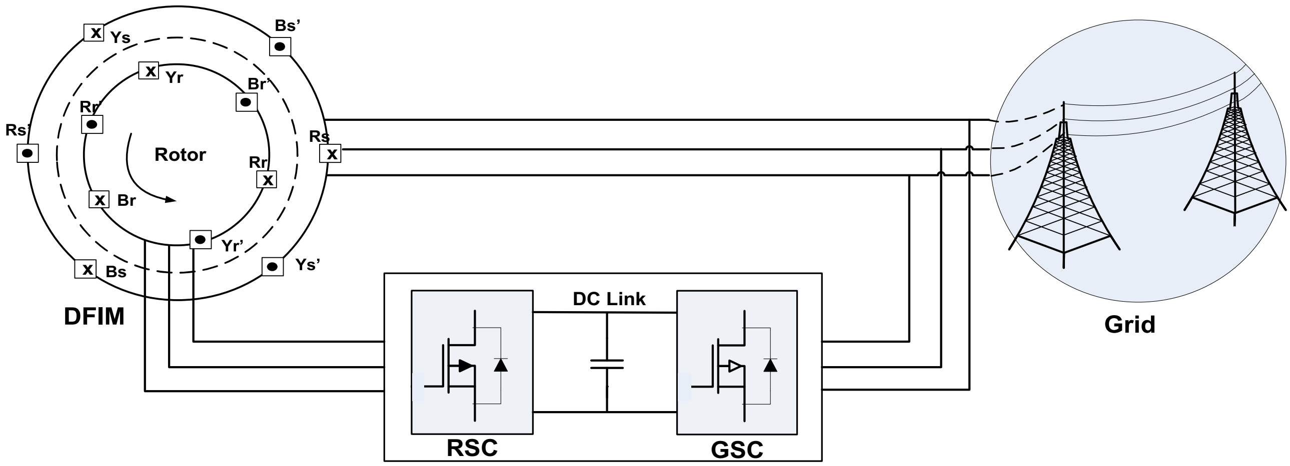

Fig. 7. Configuration of power converters in doubly fed induction machine.

Table 5
Comparison of synchronous machine and doubly fed induction machine in HEES.

Features	*Synchronous machine*	*Doubly fed induction machine*
Excitation	*The synchronous machines possess low voltage and low current DC field in the rotor circuit compared to DFIM* [149].	*The DFIM possess three-phase AC power for exciting the machine.*
Starting	*Inherently not self-starting. They require some external means to bring their speed close to synchronous speed to before they are synchronized. Otherwise they need damper winding*	*Self-starting machine*
Speed	*Runs at synchronous speed*	*Runs at sub-synchronous / synchronous / super-synchronous speed.*
Speed Variation	*Wide range of speed variation*	*Limited speed range ± 30%*
Power generation	• *Power generation is possible at synchronous speed* • *No possibility of power generation from rotor circuit*	• *Power generation is possible in sub / super synchronous speed.* • *Power generation is possible from both stator and rotor circuit under super synchronous mode.*
Control	*Simple*	*Complex*
PE contribution	*Possible to operate the machine without PE converters*	*Crucially depends on PE converter*
Rating of PE converter	*The generated power fed to the grid through the converters. Hence, the rating of the converters is same as the machine rating* [150].	*The slip decides the rating of the converter, which makes the converter partially rated* [141].
System cost	*The installation cost is more due to full rated power converters.*	*The installation cost is less due to partial rated power converters* [80].
Size	*Comparatively smaller than DFIM*	*The size of the machine is larger as it bears three-phase current in the rotor.*
Efficiency	*Average*	*The DFIM has high overall efficiency and also it can act as a synchronous machine at zero frequency excitation control.*
Power Factor	*Variation of d.c excitation provides power factor control and this can be obtained with or without PE circuit*	*Injection of variable AC voltage and frequency to rotor provides power factor control. This can be obtained only with the help of PE converters.*
Power quality	*It can produce constant output voltage. This machine has the unique characteristics of operating under any power factor. This makes it being used in the power factor improvement.*	*The DFIG could produce more active power than the synchronous generator. Also decoupling of active and reactive power is also possible* [144,151].
Operating performance of machine under partial load	*Synchronous machines operate at rated power to yield maximum efficiency.*	*The DFIM can be operated in partial load due to its controlling performance* [152].
Operating performance of machines under grid failure	• *The voltage gets drooped under grid failure* [116]. • *Synchronous machine is not possible to operate without disconnection during grid failure.* • *Power oscillation is lesser in a weak and strong network.* • *Synchronous machine cannot respond fast throughout the demands of power.*	• *During grid failure the voltage increases dynamically and the machine losses its control.* • *During grid failure, the DFIM reactive power injection that takes place using the crowbar circuit to operate without disconnecting from the network* [153–162]. • *DFIG has less active power oscillations and more reactive power oscillations in the weak and strong network.* • *Stability performances are better in DFIM during low and high-speed operation also DFIM can respond faster throughout the demand of active and reactive power in the network* [80,99,113,141].

Additionally, variable speed turbine benefits in flexibility and provide more chances to allocate the produced energy in the plant [157]. Hence, reservoir area could also be reduced in the same capacity plant which consequence benefits in the environmental impacts. Moreover, it is observed that Francis turbine has more potential in variable speed operation as compared other hydraulic turbines [158].

The adjustable speed drives have the capacity to provide high turbine efficiency during extended cavitation-free operating range of the plant [159,160]. In addition, it provides grid stabilization along with high dynamic plant power control. In small hydro plants, the output power varies in accordance with the variation of water flow and trends to create the unbalance in the output power. This instability in the renewable energy sources and the varying demand of the consumers cause power fluctuation in the network. A controllable instantaneous power balancing source is required to satisfy the energy demand and maintain the stability [161,162]. The above requirement can be achieved through pumped storage plant which is one of the most cost effective large-scale technologies [124]. The important significance of pumped storage power plant is uninterrupted power delivery during grid failures and in peak hours [49]. During the strong wind or sunshine day or off-peak period, the excess power utilized in pumped storage plant for pumping water to an upper reservoir. Also during peak period, water released to the lower level reservoir through hydroelectric turbines for electricity generation [164,164]. The pumped storage plant can configure in different ways like reversible or irreversible turbines with fixed or variable distributor. The operation with variable speed is necessary for increasing the overall efficiency of HEES [139]. All these variable speed operation of generating mode or pumping mode in HEES can be effectively driven only through power electronic circuits.

4.1. Hydro power plants: Generating Mode

During the past four decades, the introduction of power electronic equipment has modernized the HEES, mainly in controlling the speed and the power quantities [158]. Power electronics based variable speed operation results in energy conservation and reduction in mechanical system by increasing the efficiency [165]. While comparing with the conventional fixed speed units, the DFIM based variable speed system used in pumped storage power plant gives various advantages like balancing the supply in accordance to the load demand on the power grid, to improve the efficiency of the generating mode, and also to improve the static and dynamic characteristics of the power system [158,166,167]. Similarly, the variable speed operation in optimized generation gives higher revenues, decoupled fast active and reactive power control, greater grid stability, grid frequency regulation and high quality power control. Finally, the variable speed power plant does not need any power system stabilizer [156,168].

All these benefits attained only through power electronic system, at the beginning PE based variable speed pump storage power plants are functioned using a synchronous machine with voltage source converter [169]. Latter, the plants are functioned using DFIM with cycloconverter and then DFIM with a voltage source converter to improve efficiency and flexibility [145,160]. Presently, power electronics based variable speed pump storage power plants are functioned using DFIM with multilevel converters for better performance. For all these advanced converters IGBT or IGCT switches with two or three level arrangements are used depending upon their power rating, [146]. To make the system control simpler and economic, diode rectifier instead of a PWM converter in rotor side can be used but it gives more harmonic distortion, to reduce the harmonic distortion significantly modified cascaded induction generator system can be used [170]. Moreover, the maximum power can be extracted from water continuously by setting the controller in variable speed turbine [171].

4.2. Hydro power plants: Pumping mode

In the conventional method, the generator's reactive power can be controlled by adjusting the excitation unit and the active power can be controlled mechanically by using a guide vane. In case of motoring mode, the active power adjustment is impossible. The recent growth in power electronics and machine technologies opens a new drift in hydro pumped storage power plant [163,172,173]. Pumped storage power plants are focused on variable speed technology to enable pumping and power control of a reversible pump turbine unit [174–176]. Contribution of PE circuits in variable speed schemes results in the reduction of cost and complexity [169]. Also the power electronics enabled pumped storage power plant has more efficiency and flexibility in operation and provides the benefits like part load operation, speed can adapt to actual water head and good dynamic response [70,152,177]. The PE converter is adequate to control the power factor as well as eliminate synchronous condenser [178]. It also provides other advantages like, increased energy efficiency of the turbine, partial elimination of cavitation effect, controllability in the pumping mode [126,179]. Various simulation studies have done in predicting the performance while designing the system [168,179–185]. Crucial achievements of PE based variable speed pump-turbines are controllability in output power, wide range of speed control, faster response, damping of power oscillations and reduction in mechanical system [163,186].

At variable speed operation in both pumping and generating modes, the active and reactive powers can be adjusted through excitation system. In DFIM, the AC excitation system is controlled by the rotor side converter and in synchronous machine is controlled by a separate controller. This active and reactive power control by various controllers [187] leads to the technical and economic benefits in pumping mode like flexibility in energy storage, startup/braking with the same excitation system, dynamic response in control, fast power settling, control the frequent starting/stopping during power fluctuation, higher pump efficiency in part load operation and higher efficiency during head variations [168,188–190]. Moreover, power electronic devices in the variable speed plant can be controlled by various techniques like parity space approach [191], maximum efficiency point tracking scheme [150], etc., The evolution of variable speed pumped storage plants are in Japan, a 17.5 MW adjustable speed pumped storage power plant demonstrated in 1981 and commissioned in 1987 by Kansai electric power company. By the same group, two separate 400 MW variable speed power plants are commissioned in 1993 and in 1995 respectively at Narude (Japan) [166]. Also, in 1990 the PE based variable speed pump storage plant is installed at Yagisawa [192]. According to a "survey of Energy Resources, 2010 in world energy council", there are around 127 GW pumped storage are presently utilized throughout the world and they rang up about 1,353 MW. The recent report of technical press indicates that minimum 15 projects are under construction to add a further 8.8 GW of capacity. Additionally a variable speed pump storage plant with the capacity of 1000 MW is under construction at THERI, India.

5. Voltage and frequency control

In HEES especially at isolated mode, the generator terminal voltage and frequency are maintained constant during speed fluctuation. Hence, these can be attained through excitation control and dump load control respectively [193,194]. Also, in self-excited induction generator and DFIG the voltage and frequency can be controlled through AC-DC-AC converter [195]. In Pico hydro application, the voltage and frequency of the single-phase self-excited induction generators are regulated through power switches and circuits with PI controller, which are actuated by a PWM controller (IC-3525) [196]. In low head micro hydroelectric plant, the PWM based VSI is used to develop the electrical characteristic of the isolated induction generator. Therefore, this voltage source inverter with PWM technique helps to improve the performance in frequency stabilization, reactive power compensation and voltage regulation [197]. Moreover, the PWM scheme is used to eliminate voltage induced in the shaft caused by the effect of parasitic coupling under high frequency [198,199].

The computer based voltage regulator is necessary to control the output voltage and power oscillation at high speed through changing automatic voltage regulator settings [200,201]. An optimal sensitivity technique has been applied in the automatic generation control to calculate the disruption factor and the reference voltage of automatic voltage regulator [202]. Meanwhile, the effects of the network constraints and the active power loss minimization should be considered before varying the automatic set point. Hence, this kind of approach is based on the theorem of non-linear disturbance. Mainly, voltage regulator can be designed using static synchronous condenser for faster response during major transients and improves the levels of secure power transfer [200]. At the same time, a newly developed control scheme named optimal tracking secondary voltage control (OTSVC) can also be used to control the output voltage and it provides the most beneficial reactive power to the interlinked power system under different loading conditions [203]. Various controllers applied to control the voltage and frequency in isolated power systems are discussed in [163,171,195–206]. Other than this, the voltage and frequency can also be maintained constant by regulating the speed of the generator [207,208].

5.1. Excitation control

The evolution of excitation systems in hydroelectric generating units is cited in [209], formerly in generating stations the excitation current is fed through the rheostat, the next stages are followed by, pilot exciter that produces the power by rotating or magnetic amplifiers for the field circuit, network power analyzers that give faster response, main exciter with controller and voltage regulator. In synchronous machine, the excitation system contains protective elements, regulators, controllers to provide controlled field current. Using an SCR based excitation system, it is possible to regulate the output voltage statically. The closed loop excitation control also called automatic voltage regulators that can maintain the voltage constant even in the disturbance on the transmission line [193,194]. In induction machine, the excitation system contains PWM bidirectional power converters, capacitor and controller. In hydro power plant, the computer controlled excitation system regulates the output voltage of the generator by sensing the output voltage [201,210–212]. Also, it can control real and reactive power by sensing the output voltage and current with network power analyzer [193,194]. In mini and Pico hydropower plant, the PI based back-to-back thyristor controllers are used to control the output voltage and frequency [206]. In distributed generation the micro hydro plants are equipped with IGBT based two stage converters for providing constant voltage and frequency [163,171,206]. Additionally, the voltage can also be controlled using adjustable solid state based static excitation system, as well as many other voltage control techniques are developed recently and discussed in [203,204,211–214].

5.2. Electronic load control or Dump load control

In HEES, the speed pertained to the demand variation that cause the frequency fluctuates. To balance the power generation and demand, the frequency control is necessary. Initially an expensive and complicated mechanical governor system is used to match the input power to the turbine according to load demand. Subsequently, electronic load control (ELC) has been introduced to balance the same [215,216]. The advantages of ELC over mechanical control are, dynamic response, less complexity in control, less maintenance and less cost. This ELC consists of resistive load, power electronic switches and controllers [217]. In micro hydro plant, the frequency is maintained constant by controlling the active power. Henceforth, a variable dump load with an electronic controller can be added into the circuit to control the active power [193,194]. Usually, the dumped load resistance will be rated to the generator rating, which can be reduced to 50% by using a technique discussed in [218]. As well as, during load variation on the grid side the voltage can be regulated by employing dump loads. For fast and reliable operation, the impedance controller can be preferred, the impedance controller consists of bridge rectifier and a chopper switch, which absorbs unused real and reactive power [219]. In induction generator, the electronic load controller (ELC) contains three leg VSC with a chopper switch, a DC bus capacitor and an auxiliary load. Besides, in ELC the gating signal can be extracted for IGBT through I cosine ∅ algorithm technique. Therefore, I cosine ∅ based ELC not only controls the load variation but also controls the frequency and voltage [220]. Also, in hydro power plants, instantaneous reactive power theory (IRPT) algorithm based ELC can be applied to control active and reactive power through controlling the voltage and frequency [221]. Moreover, ELC has the ability to balance the current under unstable load conditions and eliminates the harmonics of the load current. Likewise, in micro hydro application, during balanced and unbalanced load conditions the frequency and the voltage can be maintained constant using ELC with IGBT based current controlled VSI and high frequency DC chopper [222,223].

In the self-excited induction generator, the external resistance can be varied using power switches through sliding mode control, which gives fast dynamic response and robust behavior [224]. The sliding mode control is easy to design for nonlinear systems and also it turns to be very appropriate for the on-off behavior of power electronic switches. Further, a new control algorithm with zigzag transformer and the power electronic circuit are available to achieve the features like maximum power tracking (MPT), harmonic elimination, load leveling, load balancing and neutral current compensation along with the voltage frequency control. Finally, it is clear that the dump load control or electronic controls are used to maintain the load constant for regulating the voltage and frequency of the generator. Though the contribution of electronic controller in HEES is more, impedance control have a few challenges like, they do not bother about the water spilling over the dam or about the generated energy dissipation in the resistor of the impedance.

6. Future trends and prospects of power electronics in HEES

From the discussion carried out in the previous sections regarding variable speed operation of HEES, it is clear that doubly fed induction machine (DFIM) with power electronics in rotor circuit is an emerging system to generate hydropower efficiently. Its contributions in hydropower and pumped storage schemes will continue in the future. Currently, many projects are under construction or planning worldwide including 4 x 250 MW TEHRI (India) pumped storage scheme, which has the largest head variation in the world. Very few publications were found about a detailed analysis of both dynamic and steady state performances of DFIM applied to HEES. Nevertheless, DFIM with rotor circuit power converter systems would be an economical alternative to the conventional fixed speed synchronous generators and, therefore, interesting work remains to be done on this system, some of them are mentioned below:

(i) *Dynamic performance of DFIM:* It is a well-known fact that power converters have a significant role for smooth starting of DFIM during pumping operation. Study of transient behavior of DFIM and the corresponding burden applied to power converters during start-up will allow power electronics

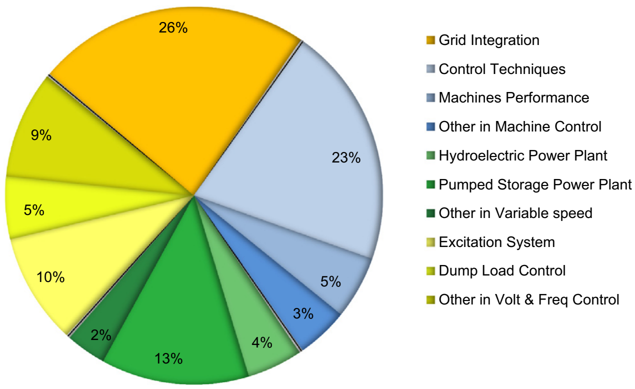

Fig. 9. Representation of power electronic contribution in various aspects of hydroelectric plant.

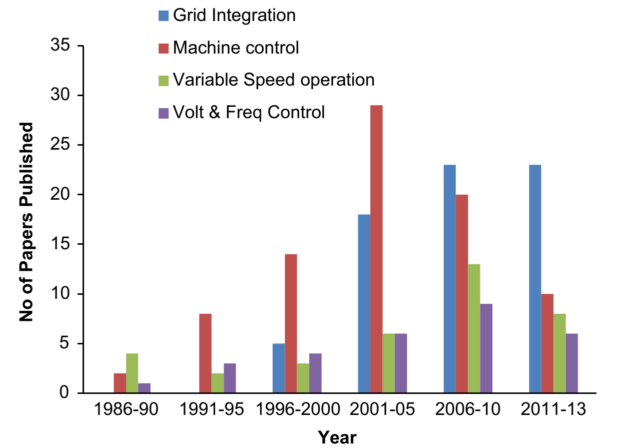

Fig. 8. An year wise paper reviewed on Power electronics in Hydro electric energy system.

engineers to design more compatible converters to these applications.

(ii) *Braking of hydro generator:* No significant contributions were available about a braking system applied to DFIM in HEES. Since pumped storage scheme need a facility to stop the generator/motor frequently with a minimum time, research on this issue will attract both the industry and academic personnel. The role of power converters to resolve this issue with minimum time delay can be discussed.

(iii) *Rating of power converters:* As discussed in section 4.2, a set of back-to-back connected power converter deals the slip power of DFIM, which is proportional to the required speed variation. For $\pm$ 20% speed variation from the rated speed of a 400MW machine, 80MW power converter is required. Research and development on high power density/capacity power converters allow us to operate the machine with a wider speed range, flexible and efficient in typical water heads.

(iv) *Power quality issues (PQ):* Various PQ issues on DFIM in wind power applications were addressed well in many publications. However, PQ issues with power converter equipped hydro generators are not addressed so far. Current trends and severity of total harmonic distortion on these generators under reactive power control and starting of pump turbines can be studied, which decide the future trends of PE circuits in the applications of HEES including harmonic filter design.

(v) *Renovation of fixed speed HEES:* There are a number of benefits in pumped storage plant (PSP) by using DFIM, described clearly in [174–176]. Economic analysis, including the cost of converters and time required for replacement, to renovate an existing PSP from fixed speed to variable speed will provide a timely decisive approach to plant managers/policymakers.

7. Conclusion

The power electronics technology plays an immense role in the development of hydroelectric power generation specifically to improve overall efficiency, controllability, grid integration, island operation, speed control in different modes and as well as for frequency and voltage control. Power electronics have been considered as an important technology, resulting in the energy conversion and reduction of mechanical system. Especially, the power electronics unit employs speed control at different level of water flow to have prominent efficiency these details discussed in the paper. Power electronics enabled pumped storage power plant have flexibility in operation and produces high efficiency also provides benefits like part load operation, speed adoption and power quality. The use of PE in mini hydro and the Pico hydro power plant has discussed in the paper. The evolutions of excitation system in the hydroelectric generation unit have summarized in detail. Comparisons of DFIM and synchronous machine topologies have discussed in the paper by considering the whole drive train into account. The growth of power electronics converters in the replacement of mechanical controllers has discussed in the paper. The perception of the paper is to idealize the application of power electronics technology in the hydroelectric energy system as discussed elaborately. Overall, the contribution of power electronics technology is enormous in hydroelectric power generation. The year wise paper classification and contribution of power electronics to hydro systems are extrapolated and are shown in Fig. 8 and 9. In addition, future trends and prospects of power electronics in HEES are also discussed clearly.

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Machine control

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