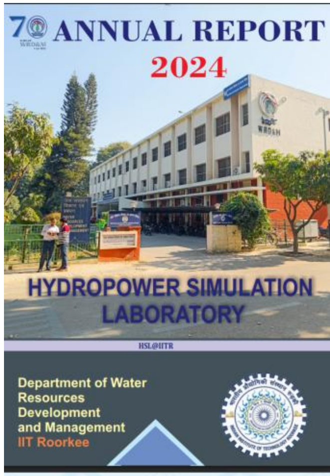

Lecture on
Electrical Energy Management (WRO-101) (part-1: generation)

by
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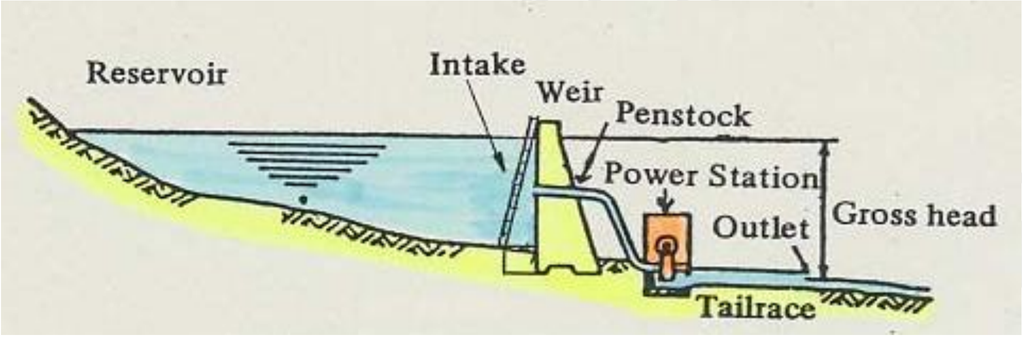
Contents

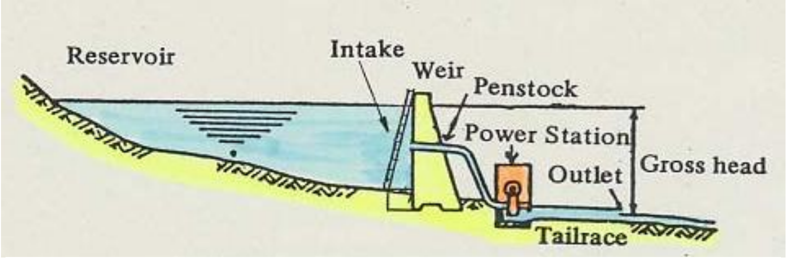
❖ Lectures/Tutorials on Electrical Energy Management: Generation, Transmission and Utilization

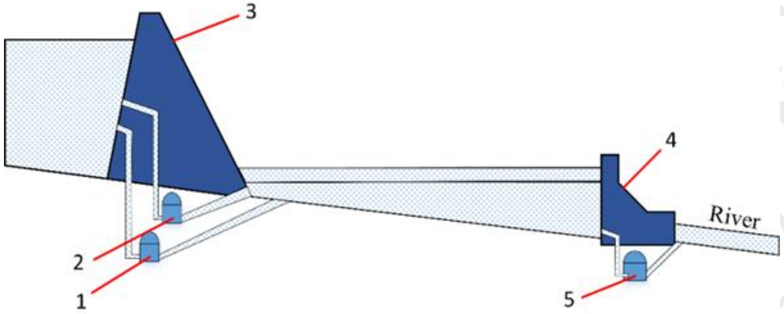
HOW IS A HYDRO-TURBINE USED TO GENERATE ELECTRICITY?

- The hydrological studies to workout the water availability, designed flow and net head available
- Power potential study, $P \propto QH$
- Selection of hydro-generating units and their capacities
- Techno-economic evaluation and tariff fixation

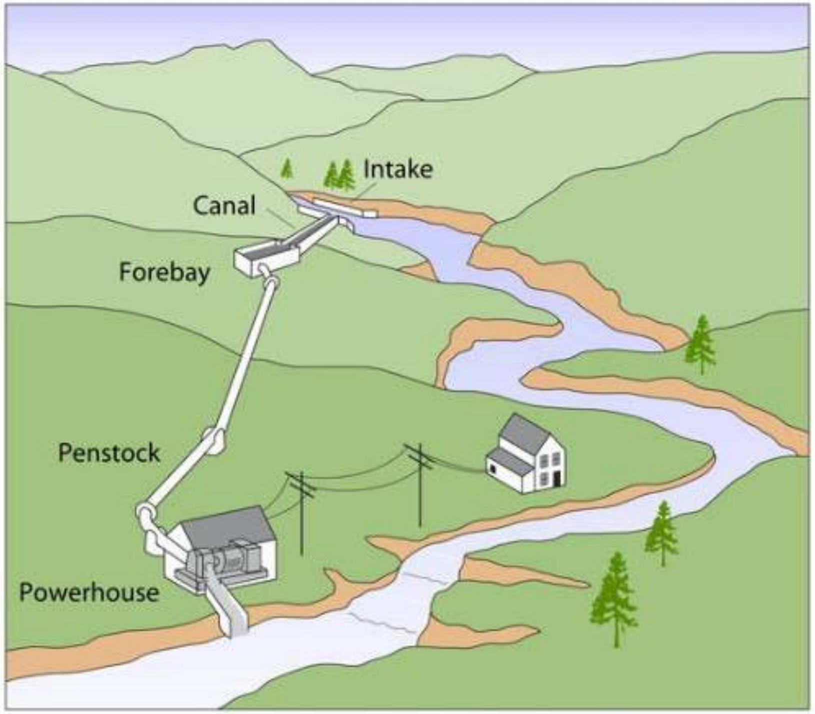


Hydro Electricity- Classification
(Reservoir type)



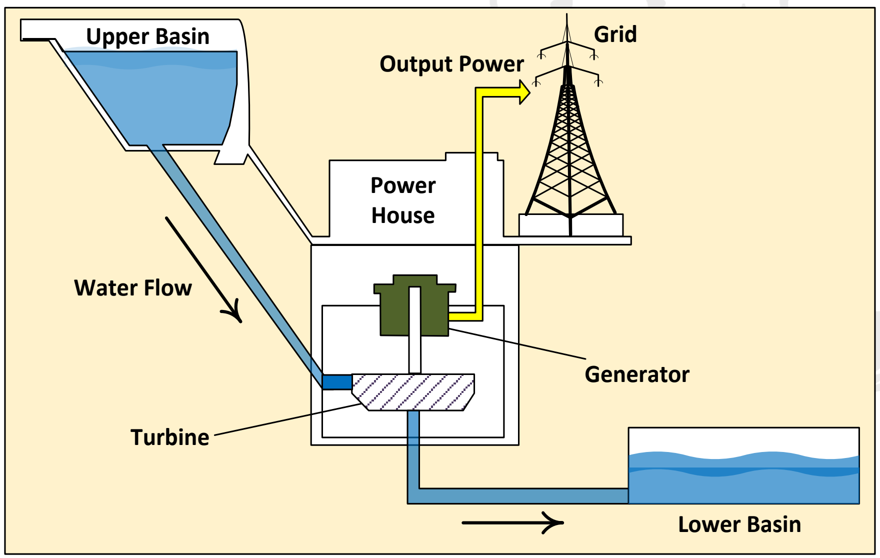


Hydro electricity- Classification
('run of river' type)

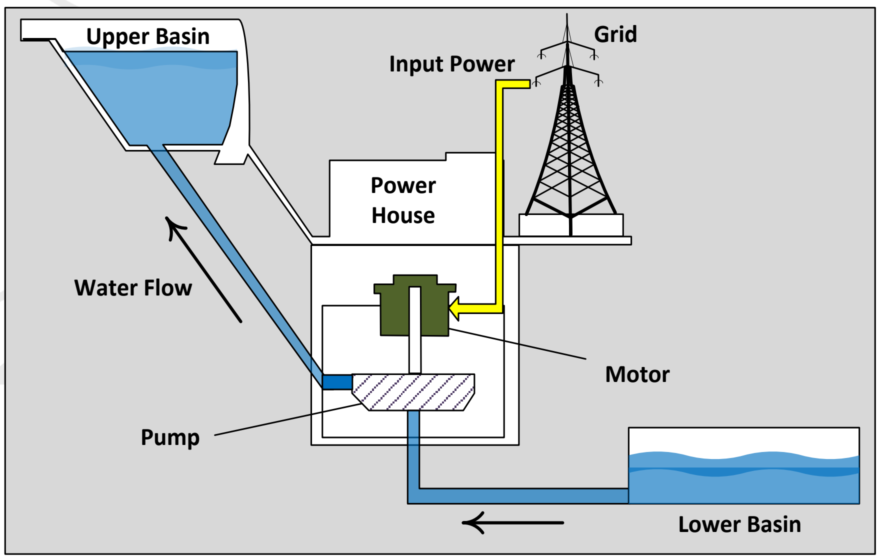


Hydro Electricity- Pumped Storage
(Importance of Pumped Storage)

- load balancing
- integrate intermittent energy sources
- pumped hydro is considered as reliable and bulk energy storage system
- Optimum use of reservoir-storage capacity
- Higher operating efficiency of base-load plants
- three operational modes, namely, pumping, idle, and generating
- total capacity of 127GW around the world and large number of PS plants are under construction with the cumulative capacity of 76GW



Power Generation (Peak Hours)



Pumping (Off-peak hours)

Classification based on capacity

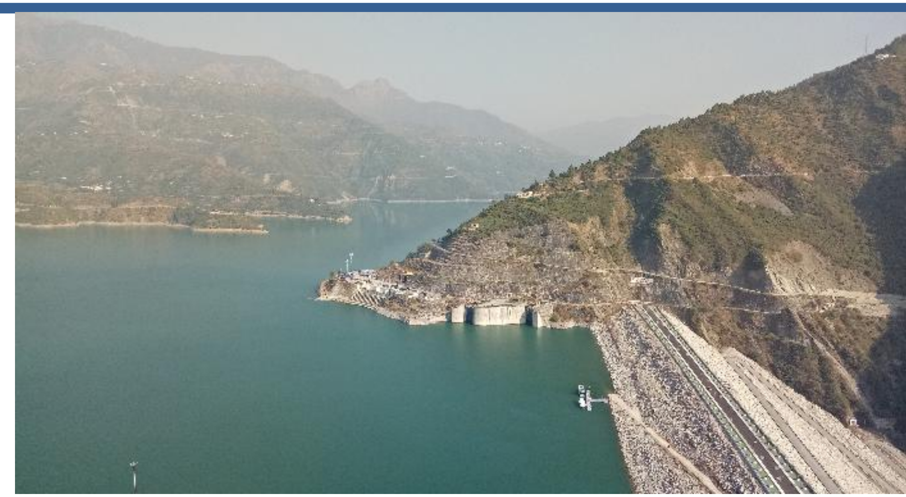
	Mini / Micro	Small	Medium	Large hydro/ PSP
Capacity	0 - 5MW	5.001 - 25MW	25.001 – 100MW	Above 100MW
Connection	Isolated/ Grid Connected	Isolated/Grid Connected	Grid Connected	Grid connected
Frequency /Active power Control	Electronic load control/speed governor	Speed governor	Speed governor	Speed governor
Voltage /reactive power Control	Motor driven/static/ brushless excitation	Motor driven/static/ brushless excitation	Motor driven/static/ brushless excitation	Motor driven/static/ brushless excitation/DFIM
Generator	Asynchronous/ synchronous	Asynchronous/ synchronous	Asynchronous*/ synchronous	Asynchronous*/ synchronous

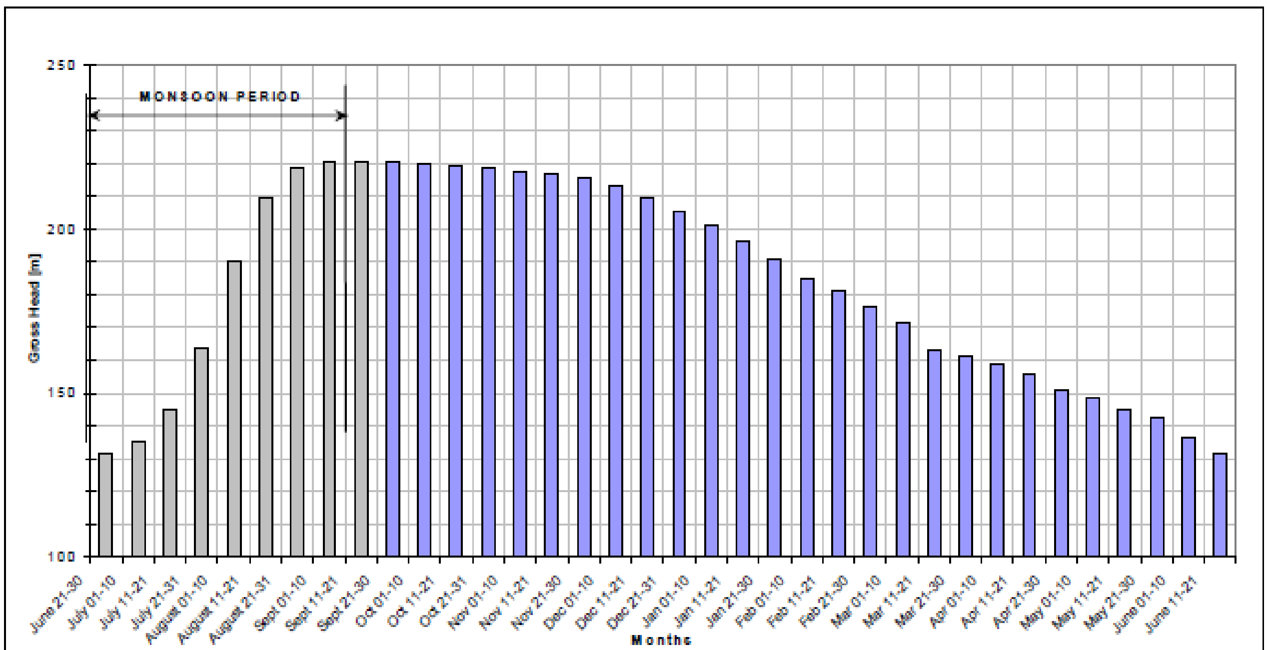
*Asynchronous machines are used in large size with the help of PE circuits.

Recent Trends in Hydro-Electric Systems

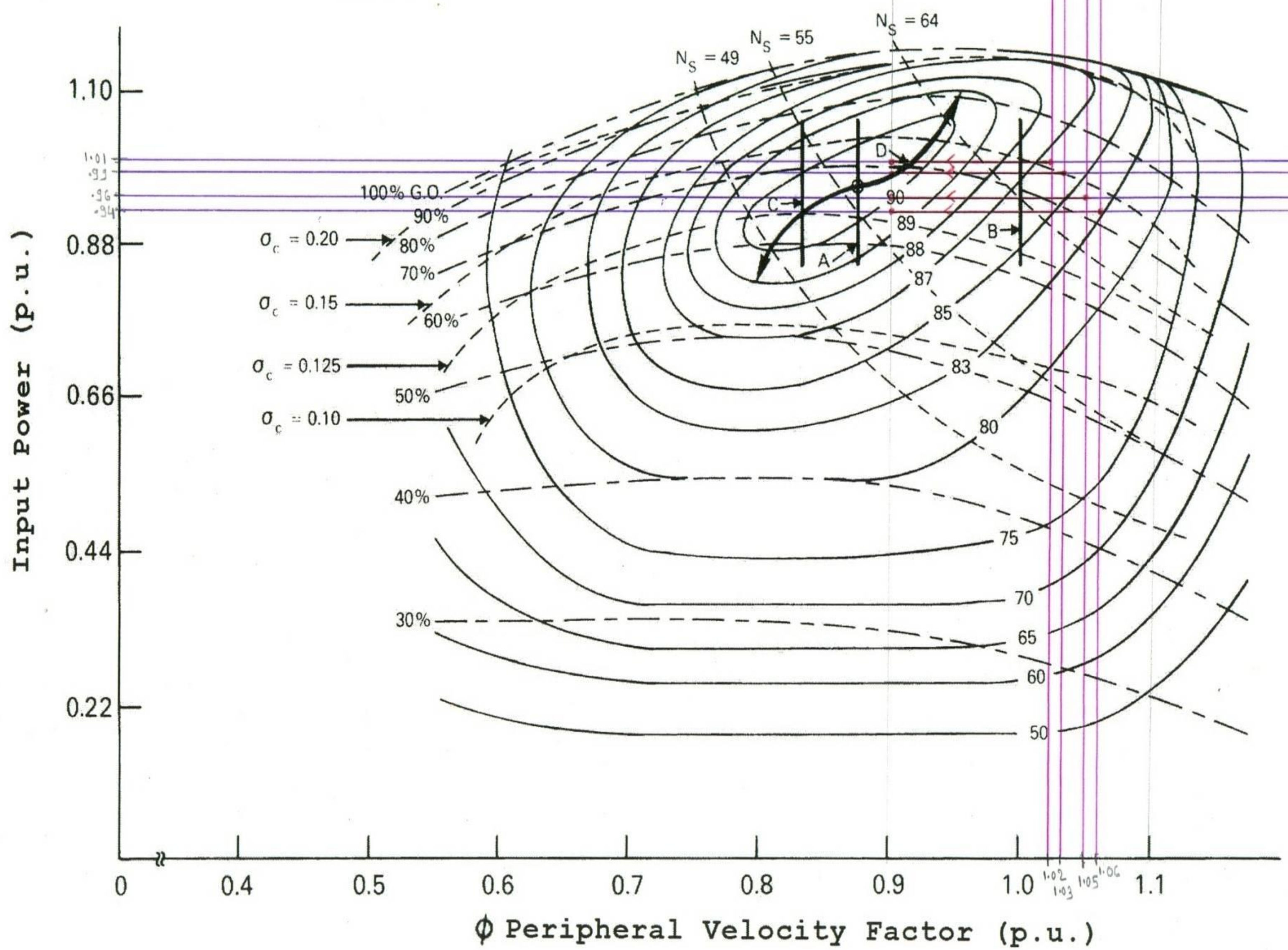
__?____ Hydropower/pumped storage plant suits to this.

- continuous operation (wide variations in water head/surplus power)
- better energy and water use efficiency
- Power controllability
- technically feasible





TEHRI PSP GENERATION (HILL CURVE)
EFFICIENCY ANALYSIS FOR FIXED & VARIABLE SPEED DRIVE



Recent Trends in Hydro-Electric Systems

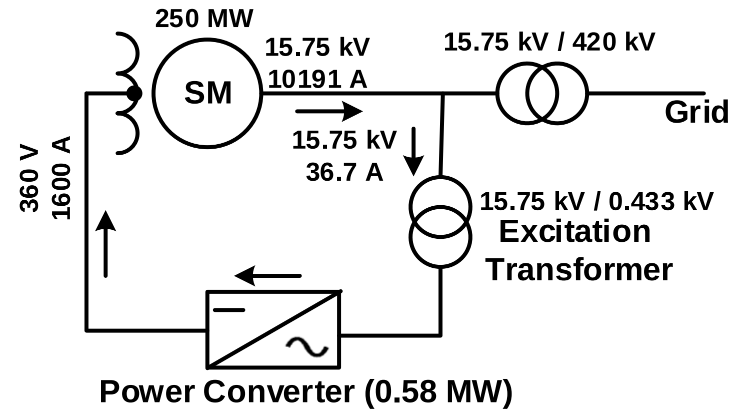
Excitation System Used in Synchronous & Asynchronous Machines at Pumped Storage Plant

Synchronous Machine

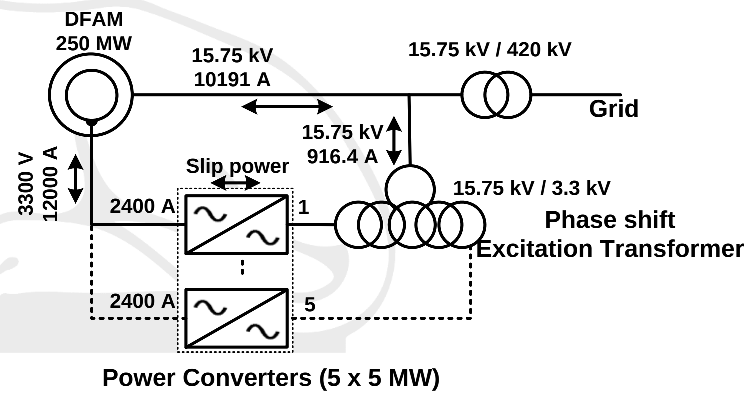
- Thyristor is usually used.
- Excitation voltage and current ratings are less.
- No real power flow via power converter.
- Easy to adopt excitation (power and control) redundancy.
- External static frequency converters (SFC) required for starting of pump- turbine.

Doubly fed Asynchronous Machine

- High frequency switching devices used in power converter. e.g. IGBT, IEGT, etc.
- Excitation voltage and current ratings are high.
- Bidirectionnel power flow in pumping and generating mode through power converter.
- Real and reactive power control through Power converter
- Power and control redundancy is challengeable.
- Excitation system converters are used for starting of pump-turbine and no requirement of SFC.
- Regenerative braking is possible through Excitation PE's.



(a) Synchronous Machine



(b) Doubly fed Asynchronous Machine

Comparison of Variable speed and Fixed speed PSP (Generation and Pumping Modes)

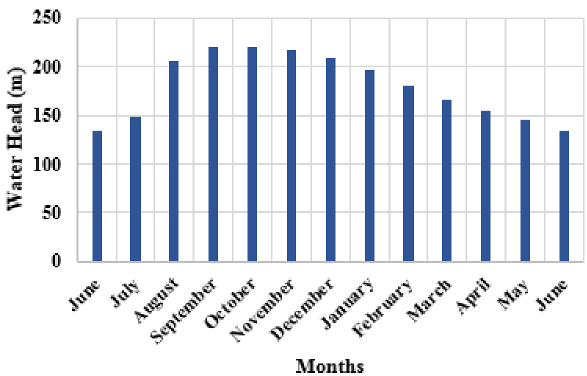


Figure. yearly water head variation

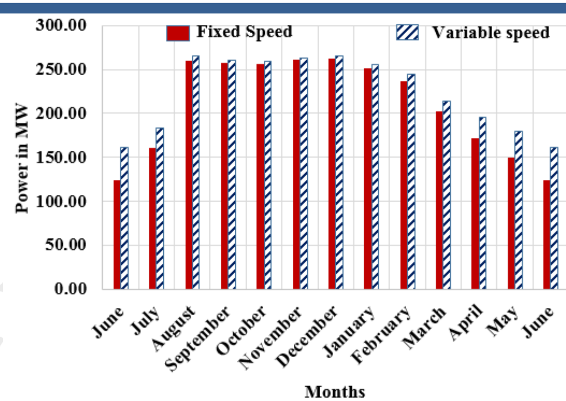


Figure. power generation at various water heads : Generation mode

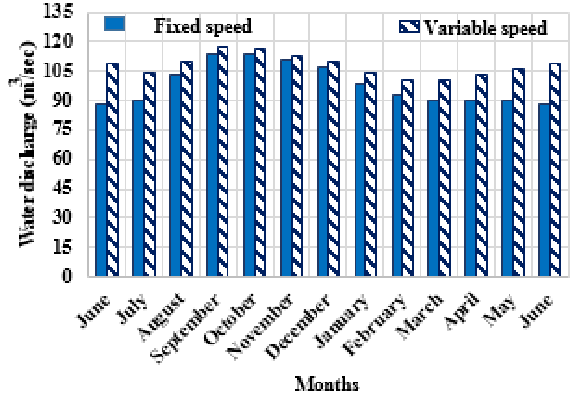


Figure. water discharge at various water heads : Pumping mode

Advantages of variable speed PSP

- Ability to generate power at lower water head level
- Increase in energy efficiency during partial generation or pumping modes.
- In generation mode, variable speed brings additional generation 6.1% than fixed speed PSP (e.g. additional generation of 441.6 MU/year for a 1000 MW (250 x 4 units) plant.)
- In pumping mode, variable speed brings additional energy storage of 8.95% than fixed speed PSP. (e.g. additional energy storage of 498.69 MU/year for a 1000 MW (250 x 4 units) plant.)

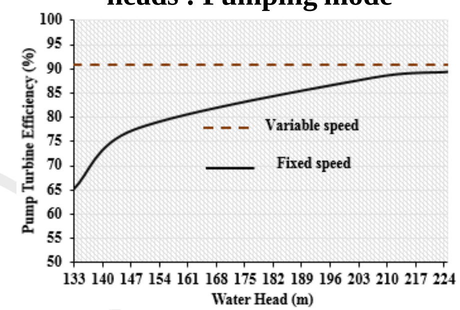


Fig. Efficiency versus water head at fixed input power (250 MW)

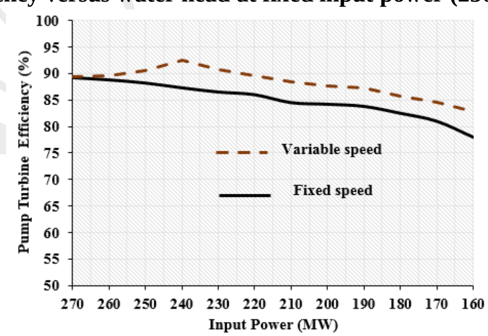


Fig. Efficiency versus input power at fixed water head (200 m)

Challenges on Hydro-Electric Systems – Case 1

(Power and Control Redundancies in Variable speed Hydro/PSP)

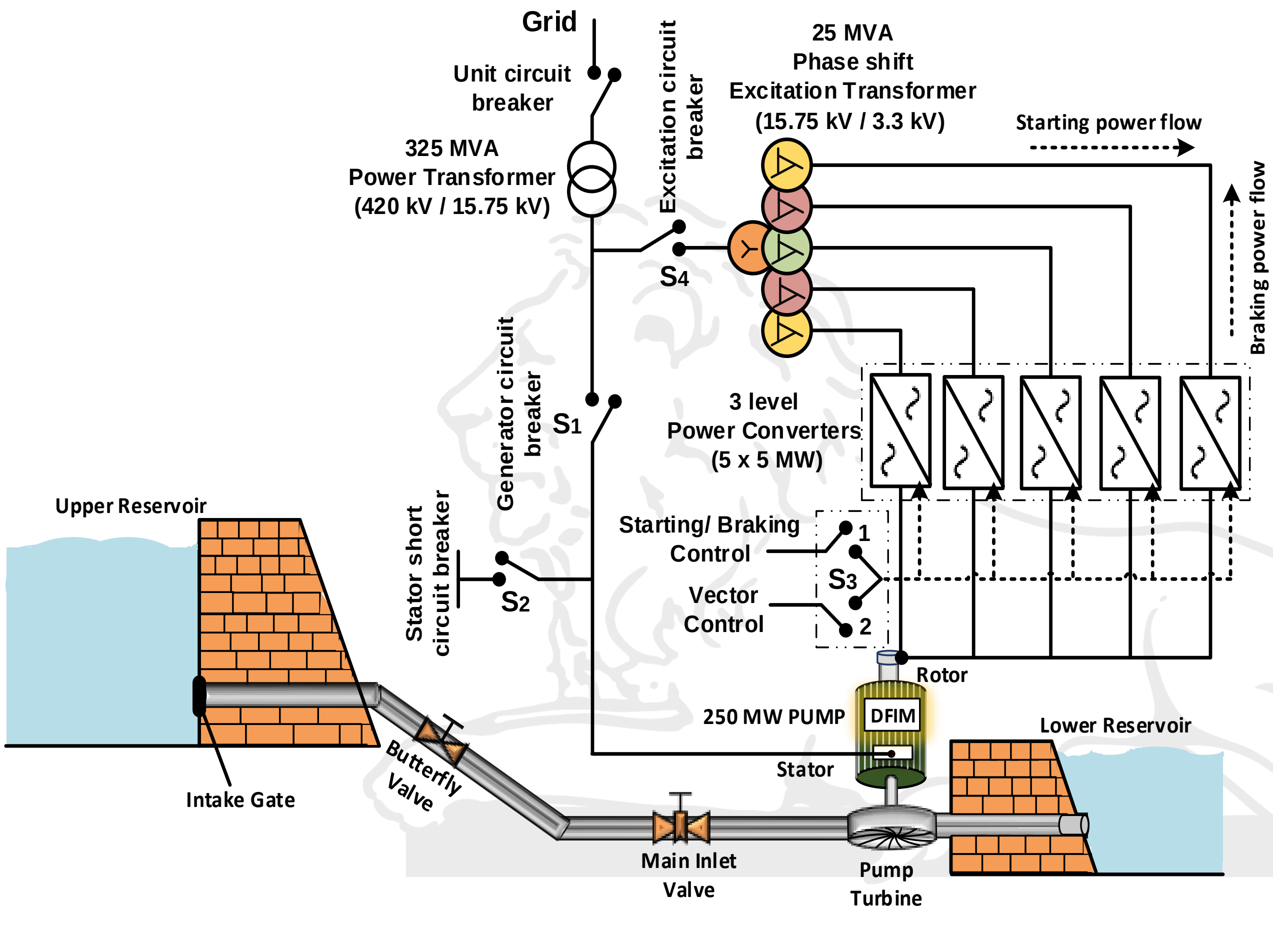


Figure: Schematic Diagram of Multi-Channel Power Converters Fed Asynchronous Generator

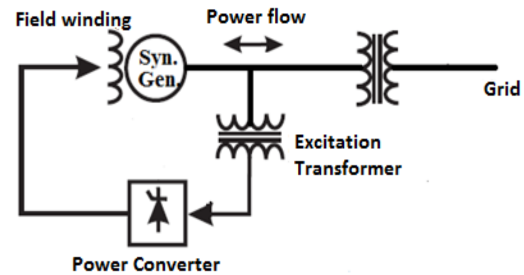


Figure: Schematic of Syn. Generator

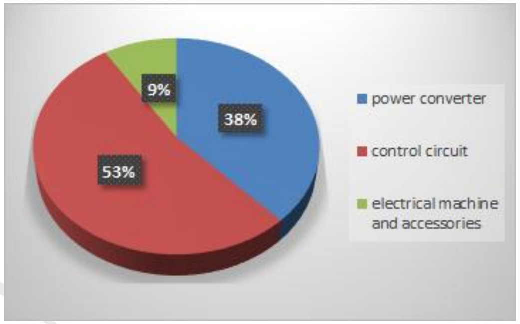


Figure: Fault distribution in Variable speed machines

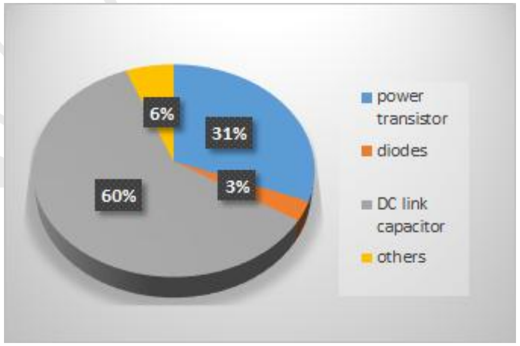


Figure: Fault distribution in power converter

Challenges on Hydro-Electric Systems – Case 1
(Power and Control Redundancies)

Contactor used in series with each power converters in parallel converter system

- The production of peak voltage is about 1.75 times rms value of maximum input voltage. However, the maximum permissible rotor voltage is limited to 1.34 times rms value of the rotor voltage (250 MW).

Detection of DC component during a fault

- High magnitude and dynamic variation of frequency in rotor fault currents are challengeable in detection

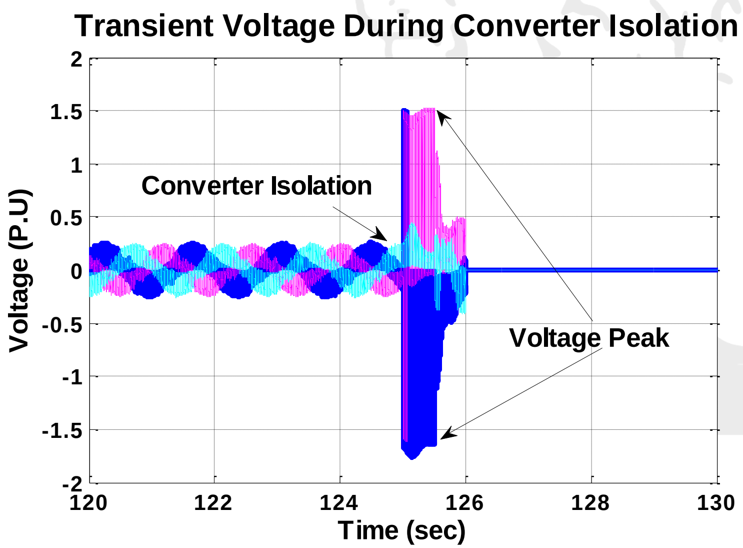


Fig. : Response of contactor used isolation and redundant operation of power converter

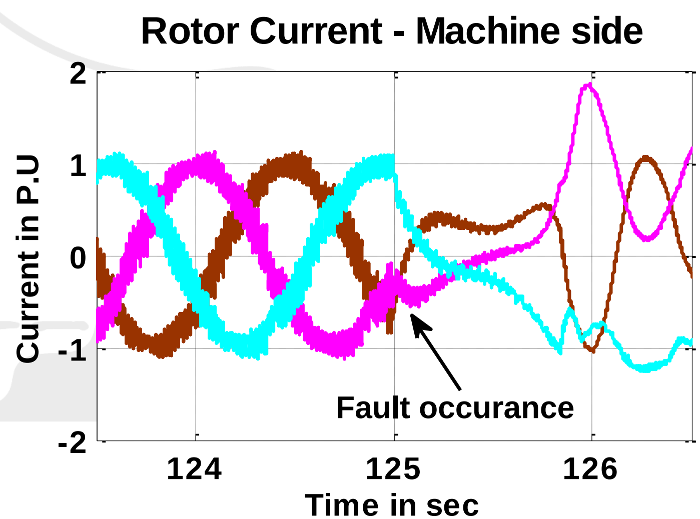


Fig. : Response of power converter fault

DFIM Subjected to Converter and Sensor Faults – Pumping Mode

Summary

Table : Power converter faults

Converter/ Fault/ mode	GRID SIDE CONVERTER						ROTOR SIDE CONVERTER					
	SDOC	SLOC	SDSC	DCSC	PPSC	PGSC	SDOC	SLOC	SDSC	DCSC	PPSC	PGSC
Super synchronous	**S**	**S**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**
Sub synchronous	**F**	**F**	**F**	**F**	**F**	**F**	**S**	**S**	**F**	**F**	**F**	**F**

SDOC - single device open circuit fault; SLOC - single leg open circuit fault; SDSC - Single device short circuit DCSC - DC short circuit; PPSC - Phase to phase SC; PGSC - Phase to ground SC; S – Survived; F – Failed

Table : Sensor faults

Mode/ Fault	Pumping					
	SGCS	SGVS	SRCS	DCVS	SS	RPC
Omission	**S**	**S**	**S**	**F**	**F**	**F**
Gain	**S**	**S**	**S**	**F**	**F**	**S**
Bias	**S**	**S**	**S**	**F**	**F**	**S**
Saturation	**S**	**S**	**S**	**F**	**F**	**F**

SGCS – Single Grid current sensor; SGVS – Single Grid voltage sensor; SRCS – Single Rotor current sensor DCVS – DC link voltage sensor; RPC - Reactive power controller; SS – Speed Sensor ; S – Survived; F – Failed

Refer: Anto Joseph, Karthik Desingu, R.R. Semwal, T. R. Chelliah, and Deepak Khare "Dynamic Performance of Pumping Mode of 250 MW Variable Speed HydroGenerating Unit Subjected to Power and Control Circuit Faults," *IEEE Transactions on Energy Conversion*, August 2017, doi: 10.1109/TEC.2017.2739132.

Economic Analysis on Power and Control Circuit Faults

- ✓ A typical fault in power converters and control circuits may result in stoppage of the unit for more than 8 hours and 4 hours, respectively.
- ✓ The rate of selling and purchase price of a unit of energy (kWh) is considered as $ 0.11 (Rs.7/-) and $ 0.05 (Rs.3/-), respectively.

Generation Mode (250 MW DFAM * 4 units)

	Energy Generation Loss (per unit/year)		Total Energy Loss (per unit/year) c = a+b	Total Energy Loss (per plant/year)	Financial loss (per unit/year) $	Financial loss (per plant/year) $
	Power Converter Fault (a)	Control Circuit Fault (b)				
1	2 MU	1 MU	3 MU	12 MU	330000	13,20,000 (Rs. 8,51,40,000)

Pumping Mode (250 MW DFAM * 4 units)

	Stored Energy Loss (per unit/year)		Total Energy Loss (per unit/year) c = a+b	Total Energy Loss (per plant/year)	Financial loss (per unit/year) $	Financial loss (per plant/year) $
	Power Converter Fault (a)	Control Circuit Fault (b)				
1	2 MU	1 MU	3 MU	12 MU	180000	720000 (Rs. 4,64,40,000)

Fault Tolerant Operation

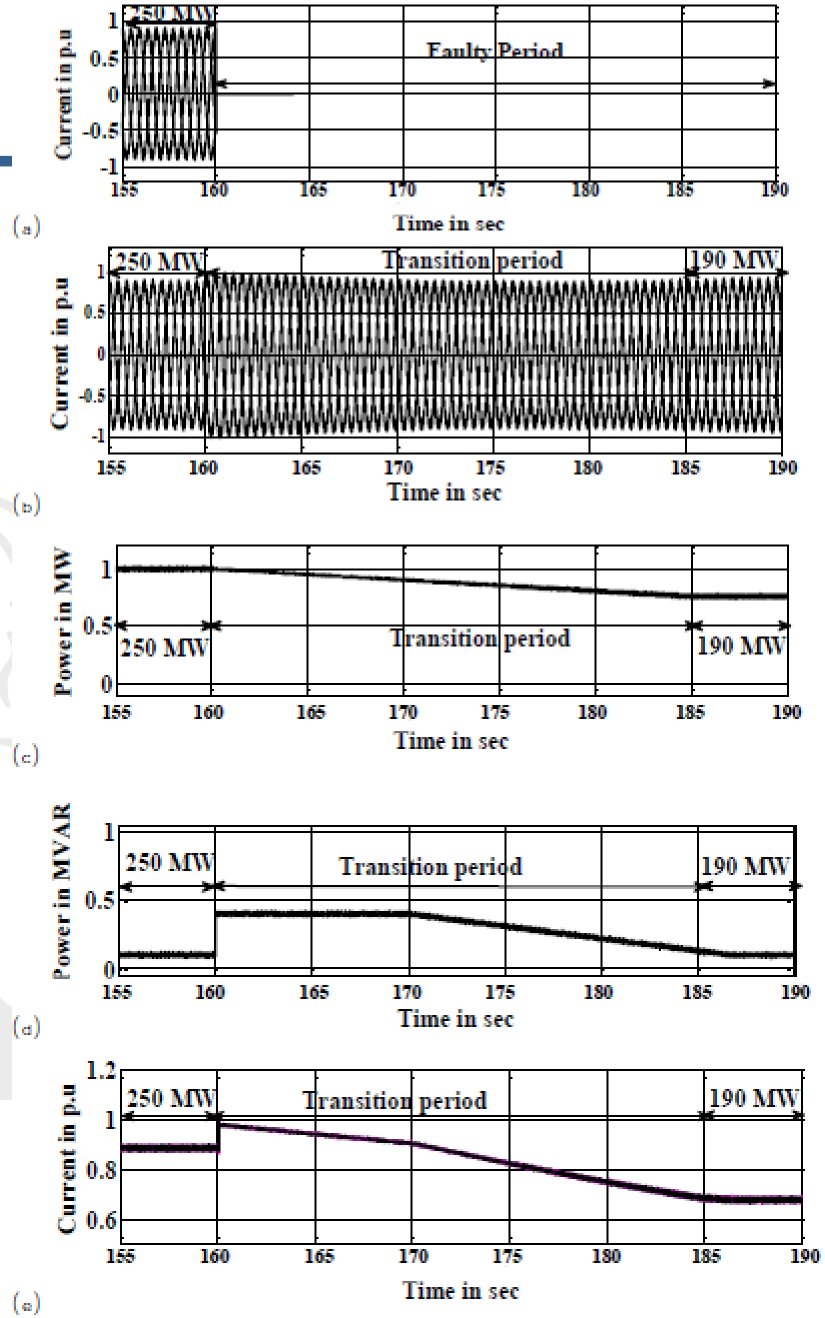


Fig. 10. Fault tolerant operation of converter open circuit fault at generation mode for a 250 MW DFIM: (a) Rotor current – faulty converter, (b) Rotor current –healthy converter, (c) Real power, (d) Reactive power, (e) Stator current

Fault Tolerant Operation- economic analysis

System	Mode of operation	Faults		Fault Status	No.of Failures /year	250 MW DFIM				
						U Period/year	Energy Storage Losses* (MU)	Financial Losses**/year (M$)	Fault Tolerant	
									Status	Benefits(M$)
Power Converter	Sub synchronous	Rotor side converter	Open Circuit Fault (SDOC, SLOC)	S	1.9940	50.59	9.87	0.59	Yes	0.51
			Short Circuit Fault (SDSC,PPSC,PGSC)	F	0.6646	16.86	3.29	0.20	NA	-
		Grid side converter	Open Circuit Fault (SDOC, SLOC)	F	0.3025	11.83	2.31	0.14	Yes	0.12***
			Short Circuit Fault (SDSC,DCSC,PPSC,PGSC)	F	0.1008	3.94	0.77	0.05	NA	-
	Super synchronous	Rotor side converter	Open Circuit Fault (SDOC, SLOC)	F	1.9940	50.59	9.87	0.59	Yes	0.51***
			Short Circuit Fault (SDSC,PPSC,PGSC)	F	0.6646	16.86	3.29	0.20	NA	-
		Grid side converter	Open Circuit Fault (SDOC, SLOC)	S	0.3025	11.83	2.31	0.14	Yes	0.12
			Short Circuit Fault (SDSC,DCSC,PPSC,PGSC)	F	0.1008	3.94	0.77	0.05	NA	-
	DC Link		Open circuit/Short circuit	F	0.007	2.19	0.43	0.03	NA	-
Control Circuit faults	Sub and super synchronous	Omission/ saturation	Speed sensor	F	0.247	5.41	1.05	0.063	NA	-
			DC link voltage sensor	F	0.247	5.41	1.05	0.063	NA	-
			Reactive power signal	F	0.247	5.41	1.05	0.063	NA	-
			Single rotor Current Sensor	S	0.247	5.41	1.05	0.063	Yes	0.063
			Single grid current sensor	S	0.247	5.41	1.05	0.063	Yes	0.063
			Single grid voltage sensor	F	0.247	5.41	1.05	0.063	NA	-
		Gain	Speed sensor	F	0.355	7.77	1.52	0.091	NA	-
			DC link voltage sensor	F	0.355	7.77	1.52	0.091	NA	-
			Reactive power signal	S	0.355	7.77	1.52	0.091	Yes	0.091
			Single rotor Current Sensor	S	0.355	7.77	1.52	0.091	Yes	0.091
			Single grid current sensor	F	0.355	7.77	1.52	0.091	NA	-
			Single grid voltage sensor	S	0.355	7.77	1.52	0.091	Yes	0.091

*** Average energy storage is 195MW//year/unit for a 250 MW DFIM**
***** Fault tolerant proposed in this paper with reduced power generation (168 MW)**
**** Financial losses are considered as $ 0.06/kWh**
U - unavailability

SDOC - single device open circuit fault
SLOC - single leg open circuit fault
SDSC - Single device short circuit
DCSC - DC link short circuit
PPSC - Phase to phase SC
PGSC - Phase to ground SC
S - Survived
F - Failed

Challenges on Hydro-Electric Systems – Case 2
(Starting and Braking of VarSpeed PSP)

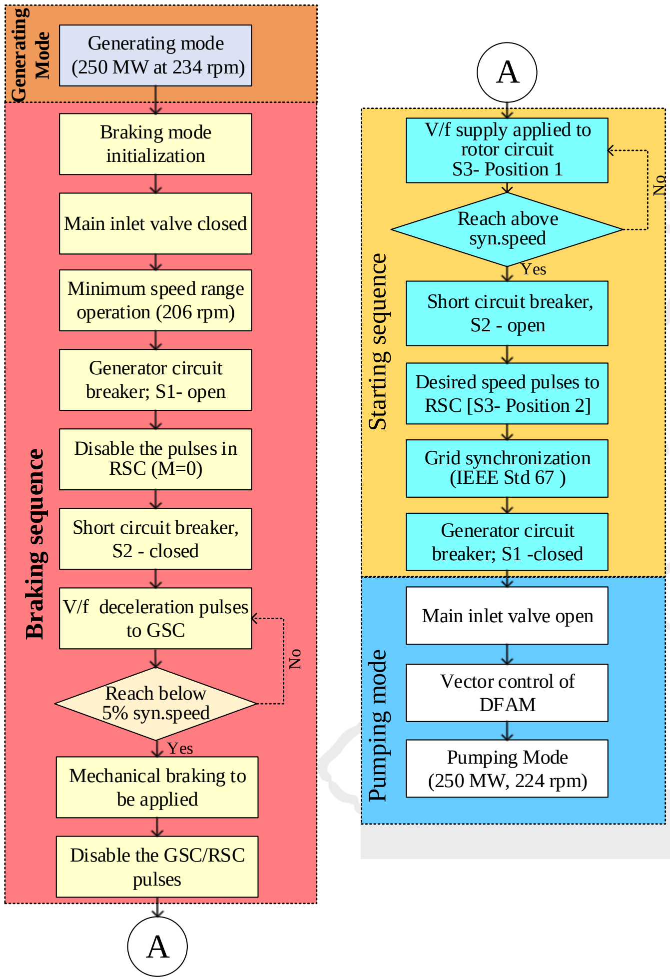
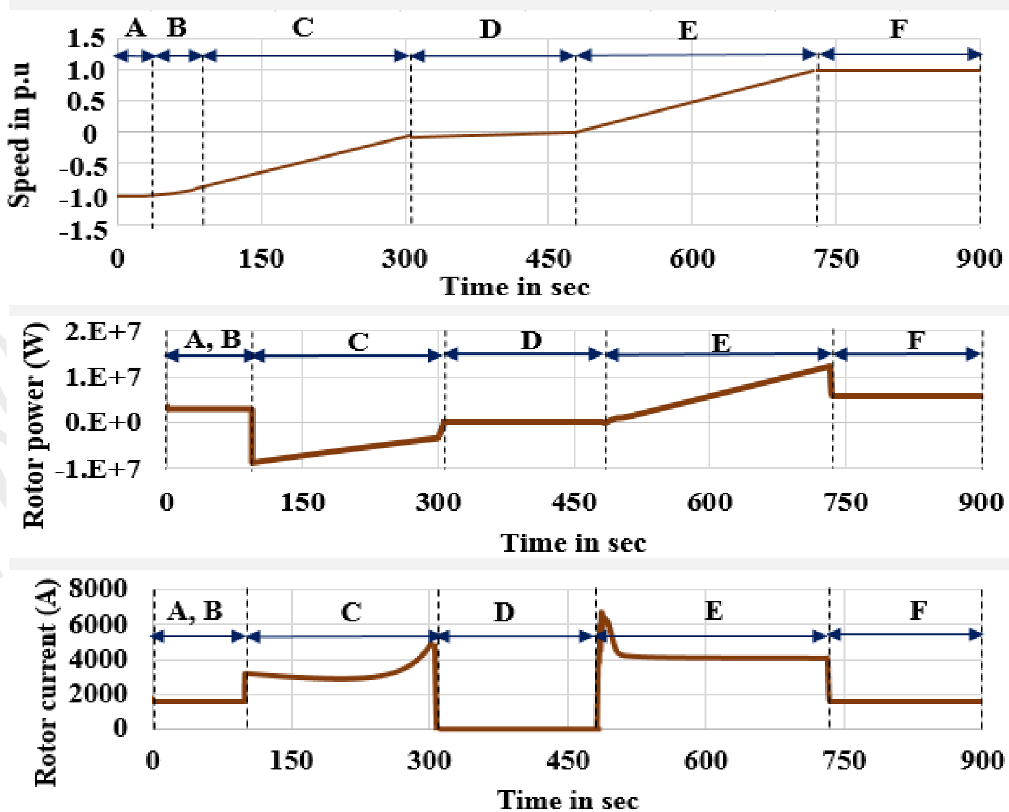


Fig. Flowchart for starting and braking sequences



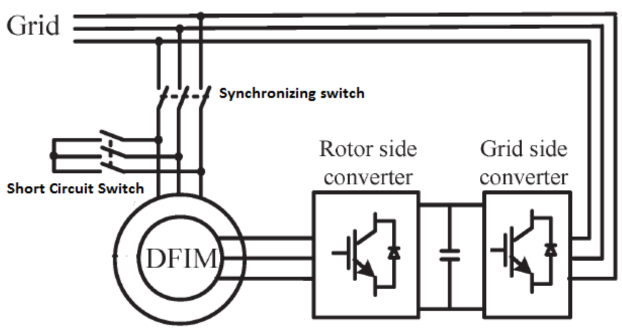
A - generation mode, B - minimum speed range at generation mode, C - regenerative braking mode, D - mechanical braking, E - smooth starting, F - pumping mode

Fig. Timing diagram during mode changeovers

Smooth Starting (250 MW DFIM)			
Real Power	8.6 MW	Time Period	250 s
Reactive Power	11.8 MVAR	Rotor Current	4200 A
Boost Voltage	430 V	Maximum Rotor Voltage	3080 V

Challenges on Hydro-Electric Systems – Case 2
(Starting -VarSpeed PSP)

- Energy Consumption during Start-up process
- Reduction of start-up transients when stator of DFIM is connected to grid



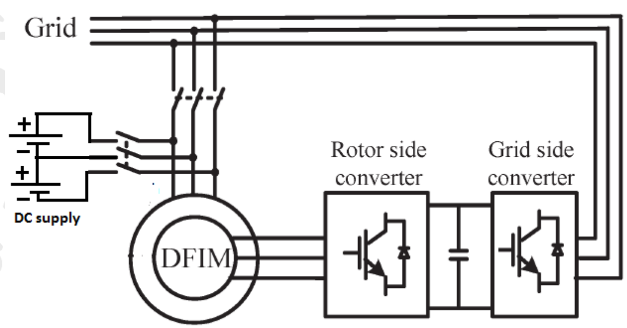
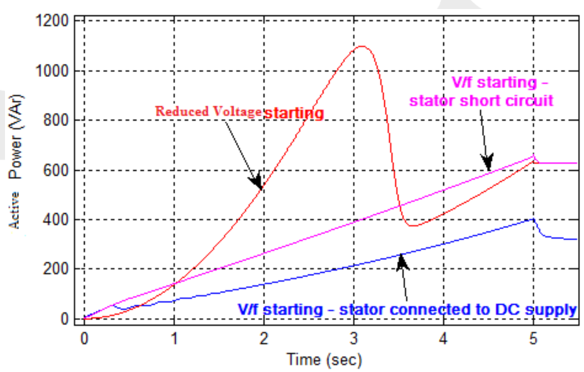
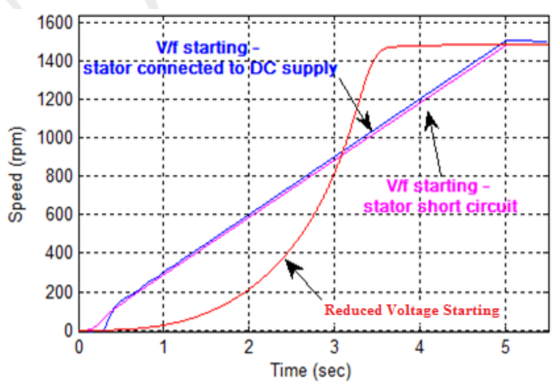


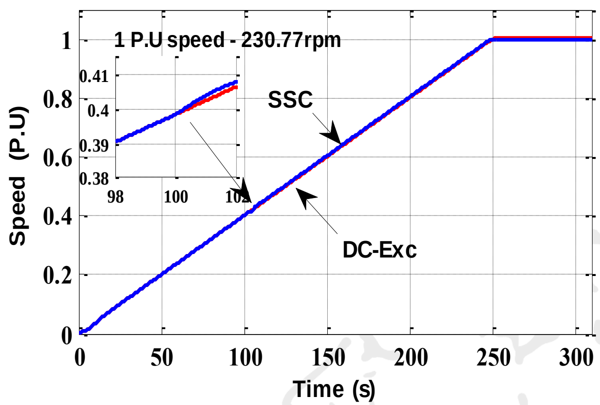
Fig. Experimental Set-up (3hp)

Experiment Results –3 HP, 415 V, 50 Hz, 4 pole DFIM (Energy Conservation)				
Mode	Stator power	Rotor power	Total power	Speed (RPM)
Stator short circuit	0	0.98 KVA	0.98 KVA	1478
Stator connected to DC supply (8.5 volts)	0.05 KVA	0.28 KVA	0.33 KVA	1500

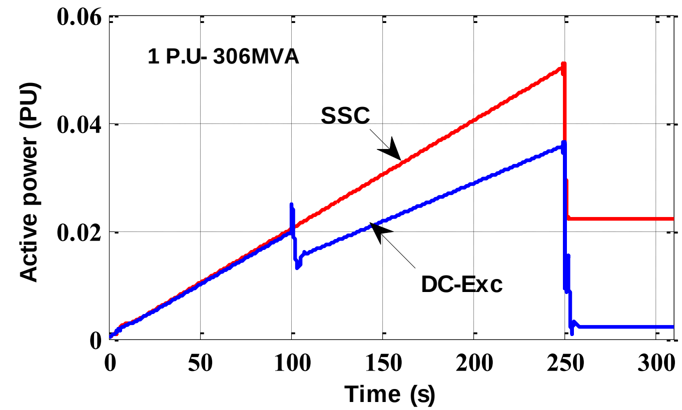




Challenges on Hydro-Electric Systems – Case 2
(Starting -VarSpeed PSP)



Speed characteristics



Apparent power characteristics

Energy calculation/ unit (306 MVA)									Energy Calculation / 4 units (306 MVA)
	Smooth starting stator short circuit (SSC)			Smooth starting with DC Excitation (DC - Ex)				Comparison of SSC Vs DC - Ex	Total energy conserved kW-hr
	zero - rated speed (0s -250 s) kW-hr	rated speed - synchronization (250 s - 310 s) kW-hr	Total (0 to 310 sec) kW-hr	zero - 40% speed (0 s- 100 s) kW-hr	40% - rated speed (100 s - 250 s) kW-hr	rated speed - synchronization (250 s - 310 s) kW-hr	Total (0 s to 310 s) kW-hr	Total energy conserved kW-hr	
Energy consumption	537.79	113.37	**651.16**	85.14	321.73	14.09	**420.96**	**230.20**	**920.82**
Starting Twice*/day	1075.58	226.74	1302.32	170.27	643.45	28.19	841.91	460.41	1841.63
Energy consumption/ month	32267.36	6802.27	39069.63	5108.21	19303.59	845.59	25257.39	13812.24	55248.94
Energy consumption/ year	387208.30	81627.25	468835.54	61298.55	231643.03	10147.13	303088.71	165746.8	662987.32

Challenges on Hydro-Electric Systems – Case 3
(Protection for Power Converters)

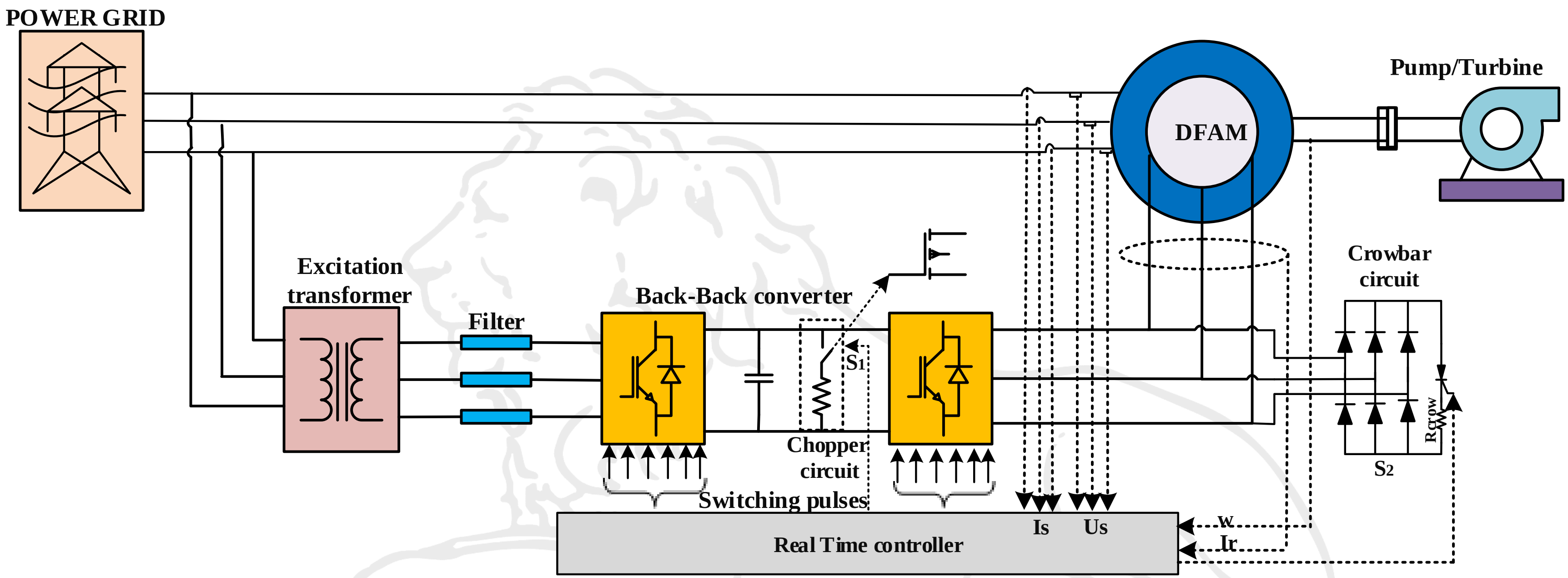
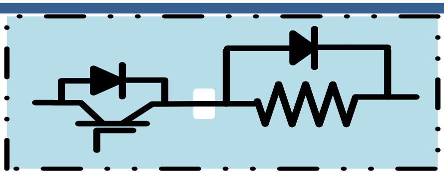


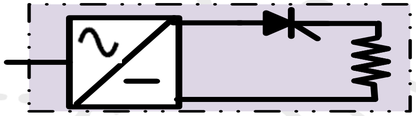
Fig. Two-Stage Protection Circuit for Multi-Channeled Power Electronic Converter Fed Large Hydro Generators

Challenges on Hydro-Electric Systems – Case 3
(Protection for Power Converters)

DC Link Chopper Protection Circuit



- DC link chopper circuit is connected in parallel to the dc link of the back-to-back power converter.
- It consists of power semiconductor device (IGBT) connected in series with power resistances and antiparallel diode connected across the resistance.
- During grid disturbances when the dc-link voltage exceeds a fixed threshold value the dc-link chopper inserts a power resistor in dc-link.
- The amount of resistance value engaged in chopper circuit is based on the rise of dc link voltage and the value of resistance engaged is controlled by applying proper PWM signal to power semiconductor device.



Crowbar Protection

Crowbar Circuit

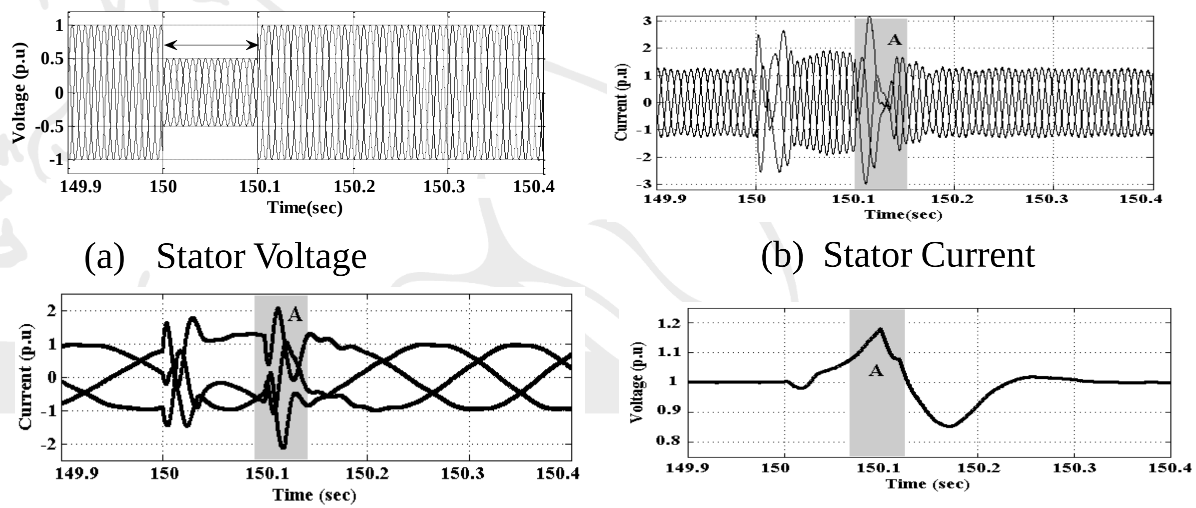
- Crowbar circuit shortens the rotor windings during severe grid disturbance thereby limiting the rotor voltage and provides an additional path for the rotor current.
- Crowbar circuit consists of diode rectifier followed by variable resistance, power devices connected to make a short circuit.

Challenges on Hydro-Electric Systems – Case 3
(Two-Level Protection for Power Electronics Converters)

<u>Operation of Two Stage Protection Circuit</u>

- DC link voltage is maintained at 5000 volts during normal operation and when grid disturbances occur the dc link capacitances limit the dc link voltage up to 5800 volts.
- If dc link voltage exceeds the above said voltage rating then dc link chopper circuit activates and control and limit till voltages reaches about 7200 volts.
- If the dc link voltage is more than 7200, crowbar protection will get activated and unit gets into shutdown.

Two Stage Protection	
DC Link Voltage	1 p.u (5000 V)
DC Link Protection	1.16 p.u
Crowbar Protection	1.44 p.u
DC Link Capacitance	18000 µF
DC Chopper Resistance	2.5 Ω
Crowbar Resistance	0.005 Ω



(a) Stator Voltage (b) Stator Current

(c) Rotor Current (d) DC Link Voltage

Fig. Momentary grid voltage sag fault for a 250 MW DFIM at generation mode (A- DC link voltage protection)

Challenges on Hydro-Electric Systems – Case 3

(Two-Level Protection for Power Electronics Converters)

Mode	Grid Disturbances	Voltage Sag	DC Link Voltage Variation	DC Link Chopper Protection	Crowbar Protection	Machine Survivability	Economic Gain* (250 MW)
Generation Mode	Momentary Voltage Sag (5 cycles)	0.1 p.u	1.006 p.u	I	I	S	-
		0.4 p.u	1.075 p.u	I	I	S	-
		0.5 p.u	1.178	A	I	S	$ 91666/-
		0.6 p.u	1.236 p.u	A	I	S	$ 91666/-
		0.9 p.u	1.692 p.u	A	A	F	-
		1.0 p.u	1.882 p.u	A	A	F	-
Pumping Mode	Momentary Voltage Sag (5 cycles)	0.1 p.u	1.009 p.u	I	I	S	-
		0.4 p.u	1.067 p.u	I	I	S	-
		0.5 p.u	1.194 p.u	A	I	S	$ 58332/-
		0.6 p.u	1.258 p.u	A	I	S	$ 58332/-
		0.8 p.u	1.523 p.u	A	A	F	-
		1.0 p.u	1.815 p.u	A	A	F	-

DC Link Voltage - 5000 volts (1 p.u) DC Link Chopper Protection - 5800 volts (1.16 p.u)

Crowbar Protection - 7200 volts (1.44 p.u)

I - Idle Mode A - Active Mode S - Survived F- Failed

- Economic gain with introduction of dc link chopper circuit protection

*Unit Stoppage Time due to Grid Disturbances = 20 minutes

*Financial losses are considered as $ 0.11/kWh for generation mode and $ 0.07 for pumping mode

- Grid disturbance occurs 10 times/year
- For Generation Mode – Only DC Link Protection Activates from 0.5 p.u. But From 0.9 Crowbar also Gets Activated.
- For Pumping Mode – Only DC Link Protection Activates from 0.5 p.u. But From 0.8 Crowbar also Gets Activated.

Note: This work is to be presented in IEEE IPEC 2018 (Japan)

How is a hydropower plant planned?

- The main purpose of SHPP is to generate electric power while facilitating water supply to irrigation fields or drinking from a storage dam.
- The hydrological studies to workout the water availability, designed flow and net head available
- Power potential study
- Selection of hydro-generating units and their capacities
- Techno-economic evaluation
- Climate change impacts of SHPP

Dependability analysis
(Case Study)

Dependability analysis

	Year	Annual Run-off	Arranged in descending order		Rank No.	% Rank $(M*100)/N_t+1$	% Dependable	Corresponding (% Dependable year)
			Annual run-off	year	M			
	2000	80251.95	80251.95	2000	1	7.69		
	2001	59859.61	76478.56	2003	2	15.38		
	2002	27753.51	71224.95	2005	3	23.08		
	2003	76478.56	68391.09	2008	4	30.77		
50%	2004	36805.37	60787.88	2006	5	38.46		
	2005	71224.95	59859.61	2001	6	46.15		
	2006	60787.88	36805.37	2004	7	53.85	50%	2004
	2007	5542.90	27753.51	2002	8	61.54		
	2008	68391.09	16443.49	2011	9	69.23		
75%	**2009**	**13556.65**	**13556.65**	**2009**	**10**	**79.92**	**75%**	**2009**
	2010	13304.77	13304.77	2010	11	84.62		
90%	2011	16443.49	5542.90	2007	12	92.31	90%	2007

% Dependability ={ $(M/(N_t+1))$ x 100}

M – order number of the discharge

N_t – total number of observation or data points

Discharge for Power Generation

S.No.	Month	Ten Day Block	No. of Days in a Block		2009 Discharge at Dam Site (cumec)
1	Jan	1	10	10	8.596
		11	20	10	8.274
		21	31	11	9.156
2	Feb	1	10	10	8.624
		11	20	10	9.219
		21	28	8	9.002
3	Mar	1	10	10	8.421
		11	20	10	8.295
		21	31	11	8.211
4	Apr	1	10	10	8.092
		11	20	10	7.567
		21	31	11	6.636
5	May	1	10	10	5.624
		11	**20**	**10**	**4.545**
		21	30	10	4.601
6	Jun	1	10	10	5.111
		11	20	10	5.649
		21	31	11	5.253

S.No.	Month	Ten Day Block	No. of Days in a Block		2009 Discharge at Dam Site (cumec)
7	Jul	1	10	10	12.173
		11	20	10	84.14
		21	31	11	100.45
8	Aug	1	10	10	22.519
		11	20	10	85.54
		21	30	10	52.717
9	Sep	1	10	10	86.87
		11	20	10	255.71
		21	31	11	26.803
10	Oct	1	10	10	165.76
		11	20	10	109.62
		21	31	11	46.963
11	Nov	1	10	10	36.183
		11	20	10	34.937
		21	30	10	40.229
12	Dec	1	10	10	25.382
		11	20	10	9.051
		21	31	11	8.484

Power Potential Study – 4 MW Erach Site

Output power $P = \eta \rho g Q H$

Head = 13m (non-monsoon) & 10m (monsoon season)

75% dependable flow of 9 Cumec corresponds to the year 2009.

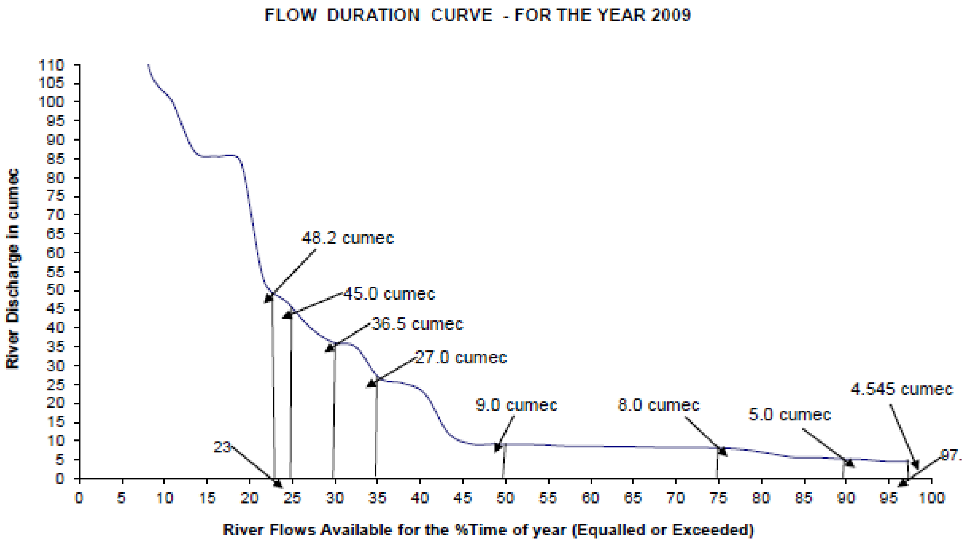


Table: Power Potential study

MW	Cumec	MU (after 10% outage)	Increase in energy (MU)	Days of full capacity generation in a year
3.2	29.66	13.68	1.07	123
3.6	33.36	14.75	1.07	123
4.0	**37.0**	**15.74**	**1.00**	**103**
4.4	40.7	16.61	0.87	82
4.8	44.49	17.32	0.87	82

Efficiency Vs Output Discharge

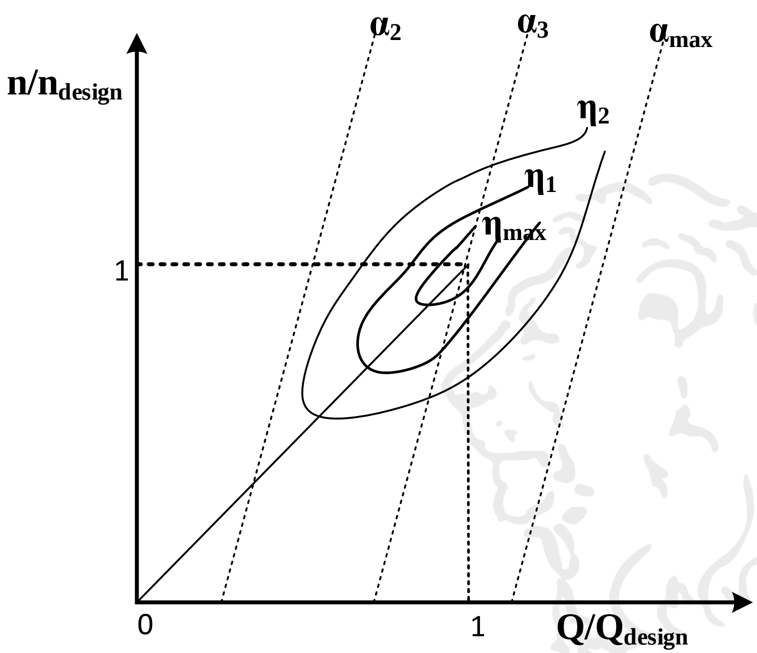


Fig. Characteristics of propeller turbine (Efficiency at variable speed)

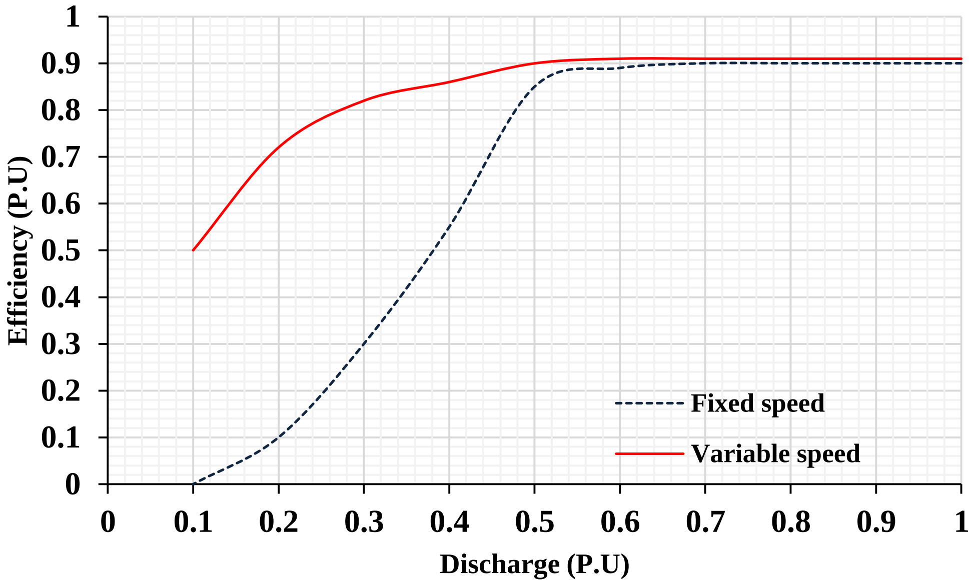
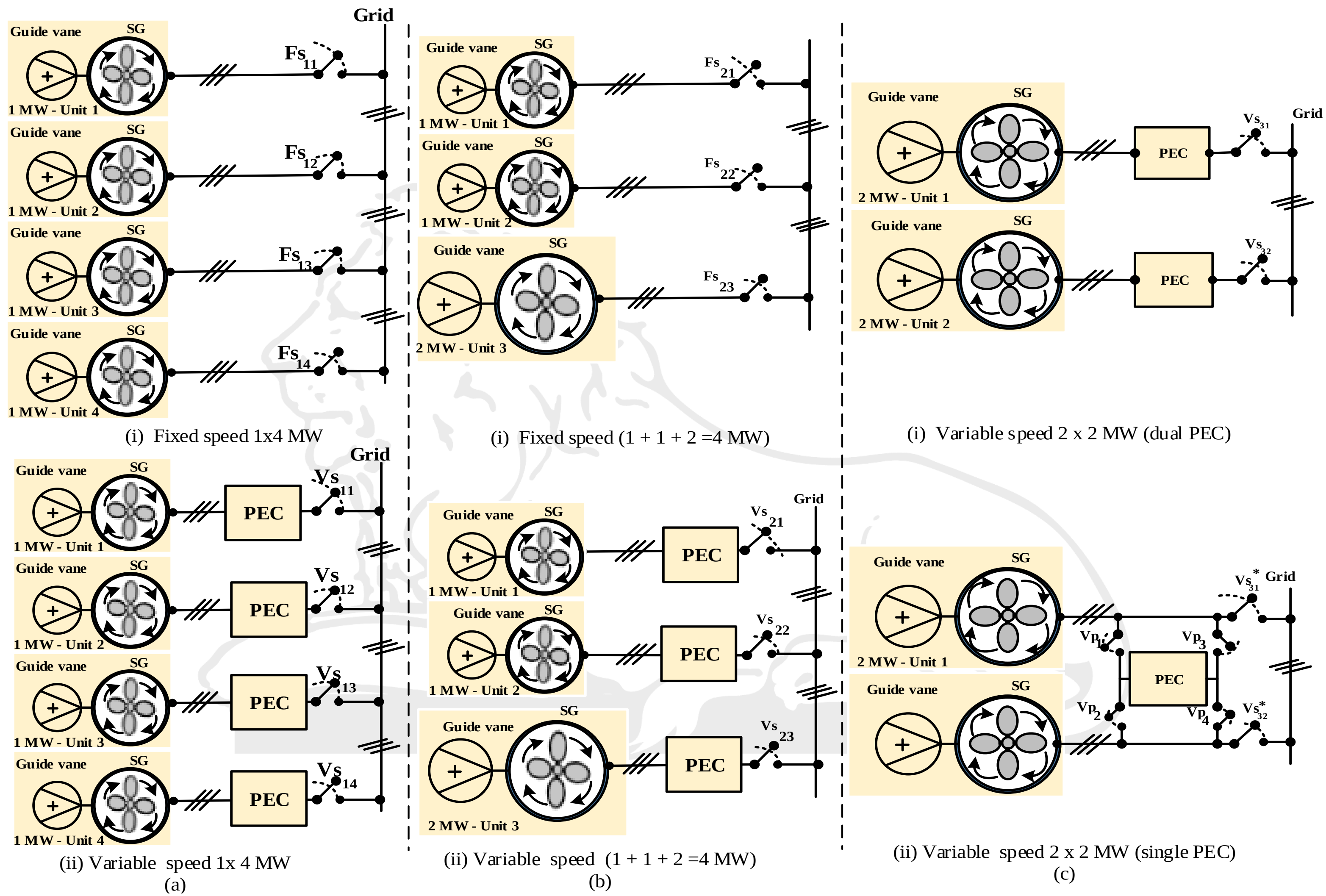


Fig. Efficiency of fixed and variable speed SHPP at wide variation in discharge

Refer: D. Borkowski and T. Wegiel, "Small hydropower plant with integrated turbine-generators working at variable speed," *IEEE Trans. Energy Convers*, vol. 28, no. 2, pp. 452–459, 2013

Different Combination of 4 MW SHPP Hydro-Sets



Monthly Discharge Versus Power Delivery Chart

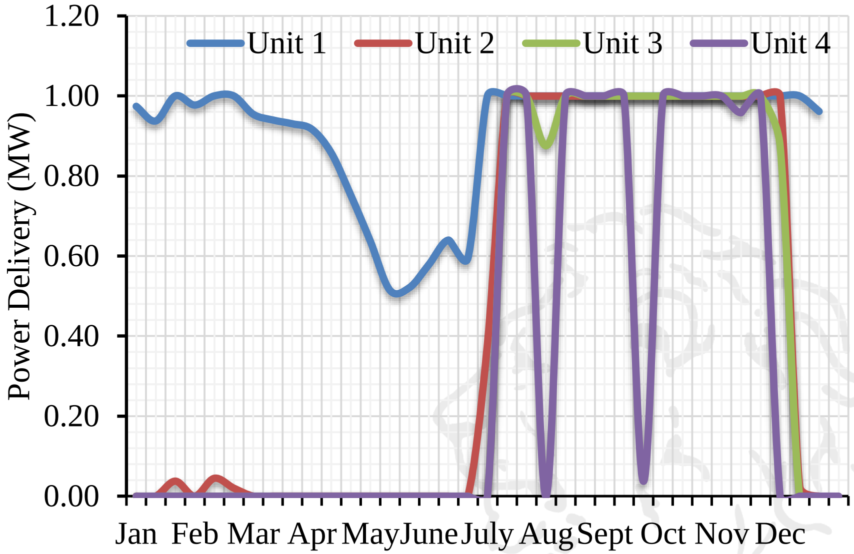


Fig. 1MW x 4 units

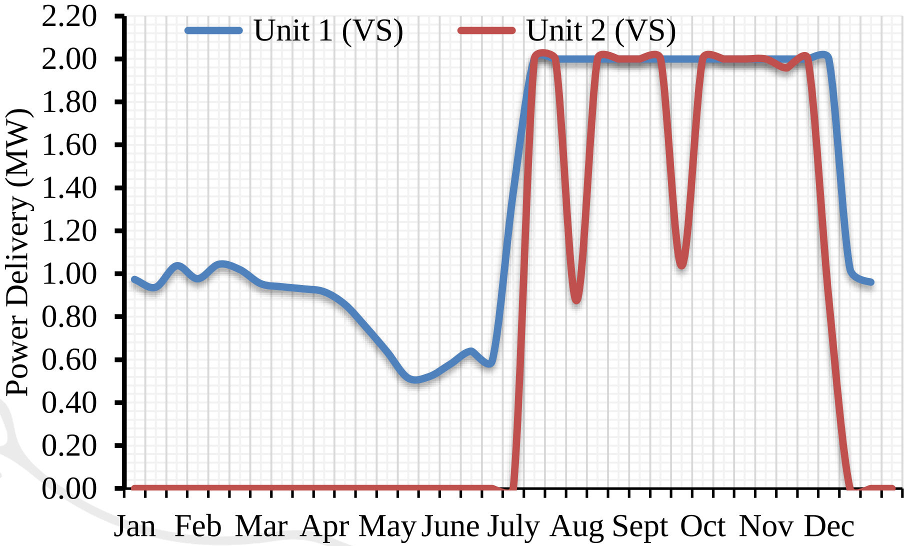


Fig. 2MW x 2 units

Advantages (2 MW X 2 Units)

- Utilization of excess discharge.
- Increased energy generation and reduced installation cost.
- Sustainable operation under varying climatic conditions

Cost Analysis of SHPP

Description of type of work	Cost per kW for Installation cost ($)	
	With two units	With four units
Civil works		
Intake(C_1)	39.77	62.84
Penstock(C_2)	18.06	29.36
Power house building (C_3)	207.46	385.25
Tail-race channel (C_4)	5.09	6.60
Electromechanical equipment		
Turbine with governing system(C_5)	132.30	240.43
Generator with governing system(C_6)	218.50	321.70
Mechanical and electrical axillaries (C_7)	103.50	138.39
Main transformer and switchyard equipment (C_8)	49.85	69.26
Power converter (C_9)	88.73	Not required
Cost per kW civil work (c_c)($)($C_1$+$C_2$+$C_3$+$C_4$)	270.38	484.05
Cost per kW of electromechanical equipment (C_m) ($)$C_5$+$C_6$+$C_7$+$C_{8+}$ C_9	592.88	769.78
Total cost per kW ($)=1.13x($C_c$+$C_{em}$)	975.48	1416.83

Refer: Karthik Desingu, T. R. Chelliah and Deepak Khare," Sustainable Operation of Small Hydropower Schemes in Changing Climatic Conditions," in proc 9th IEEE International Conference on Asia-Pacific Power and Energy Engineering, Bangalore, November 2017

Challenges on Hydro-Electric Systems – Case 4
(Large Hydrogenerators Operate at Continuous Over-Loads)

Problem Description:

- I planned a project of large hydropower plant with multiple units, each of 250MW (fixed speed)
- During construction, I felt the need to make provision for 20% continuous overload operation of the project when sufficient water is available, 45 days approximately
- What is my selection on hydro-generating equipment and its accessories which suit the plant economically and technically (assume 0.9 pf)?

Answer:____________

Analysis of plant operation:

Various data e.g. order specifications for electro-mechanical works (turbine, generator and associated auxiliaries), turbine model test report, quality plans followed for equipment suppliers, field efficiency testing of turbine and generator, operational data of units (including temperature-rise on equipment), test reports of E&M equipment.

Temperature-rise in stator

Date	Stator Winding Temp. (^{o}C)												Stator Core Temp. (^{o}C)												Stator Teeth Temp. (^{o}C)												Cold Air Inlet Temp. (^{o}C)						Hot Air Outlet Temp. (^{o}C)					
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	1	2	3	4	5	6
21-06-14	106	105	107	110	107	107	108	105	108	109	105	107	79	79	80	79	78	77	80	80	79	79	80	78	79	79	79	77	79	78	79	78	79	78	81	80	35	36	35	34	37	34	72	71	71	71	70	70
22-06-14	106	105	107	110	107	107	107	105	108	109	105	107	79	79	80	79	78	77	80	80	79	79	80	78	79	79	79	77	79	78	79	78	79	78	81	80	35	36	35	34	37	34	72	71	71	71	70	70
23-06-14	105	105	106	109	106	106	107	104	107	108	104	106	78	78	79	78	77	76	79	79	78	78	79	77	79	78	78	76	78	77	78	77	78	77	80	79	35	36	35	34	37	33	71	70	70	70	70	69
24-06-14	106	105	107	109	107	106	107	104	107	108	105	106	79	78	80	78	78	77	79	80	78	78	79	77	79	78	78	76	78	77	78	78	79	77	81	79	35	36	35	34	37	34	71	70	70	70	70	69
25-06-14	107	106	107	110	108	107	108	105	108	109	106	107	80	79	80	79	79	78	80	81	79	79	80	78	80	79	79	77	79	78	79	79	79	78	82	80	36	37	36	35	38	34	72	71	71	71	71	70
26-06-14	107	106	107	110	108	107	108	105	108	109	106	107	80	79	81	79	79	78	81	81	79	79	80	79	80	79	79	77	80	79	79	79	80	78	82	81	36	37	36	35	38	34	72	71	71	71	71	70
27-06-14	107	107	108	111	108	107	109	106	109	110	106	108	80	80	81	80	79	78	81	81	80	80	81	79	80	80	80	78	80	79	80	79	80	79	82	81	37	37	36	36	39	35	73	71	72	72	71	71
28-06-14	108	107	108	111	109	108	109	106	109	110	107	108	81	80	81	80	79	79	81	81	80	80	81	79	81	80	80	78	80	79	80	80	80	79	83	81	37	38	36	36	39	35	73	72	72	72	72	71
29-06-14	108	107	109	111	109	108	109	107	109	110	107	108	81	80	81	80	80	79	81	82	80	80	81	79	81	80	80	78	80	79	80	80	80	79	83	82	37	38	36	36	39	35	73	72	72	72	72	71
30-06-14	107	106	108	110	108	107	108	106	108	109	106	107	80	79	81	79	79	78	80	81	79	79	80	78	80	79	79	77	80	78	79	79	80	78	82	81	36	37	36	35	38	35	72	71	71	71	71	70
01-07-14	107	106	107	110	108	107	108	105	108	109	106	107	80	79	81	79	79	78	81	81	79	79	80	79	80	79	79	77	80	79	79	79	80	78	82	81	36	37	36	35	38	35	72	71	71	72	71	71
02-07-14	106	105	107	109	107	106	107	105	107	108	105	106	79	79	80	79	78	77	80	80	79	79	80	78	79	79	79	77	79	78	79	78	79	78	81	80	36	37	36	35	38	35	72	71	71	71	71	70
03-07-14	107	106	107	110	108	107	108	105	108	109	106	107	79	79	80	79	78	77	80	80	79	79	80	78	80	79	79	77	79	78	79	78	79	78	81	80	36	37	36	35	38	35	72	71	71	71	71	70
04-07-14	108	107	108	111	109	108	109	107	109	110	107	108	81	80	81	80	80	79	81	81	80	80	81	79	81	80	80	78	80	79	80	80	80	79	83	81	37	37	36	36	39	35	73	72	72	72	72	71
05-07-14	109	108	109	112	110	109	110	107	110	111	108	109	82	81	82	81	81	80	82	82	81	81	82	80	82	81	81	79	81	80	81	80	81	80	84	82	37	38	37	36	39	36	74	73	73	73	73	72
06-07-14	108	108	109	112	109	108	110	107	110	111	107	109	81	81	82	81	80	79	82	82	81	81	82	80	81	81	81	79	81	80	81	80	81	80	83	82	37	37	36	36	39	35	74	72	72	73	73	72
07-07-14	108	108	109	112	109	108	110	107	110	111	107	109	81	81	82	81	80	79	82	82	81	81	82	80	81	81	81	79	81	80	81	80	81	80	83	82	37	38	36	36	39	35	74	72	72	73	72	72
08-07-14	108	107	109	111	109	108	109	107	109	110	107	108	81	80	82	80	80	79	82	82	80	80	82	80	81	80	80	78	81	80	80	80	81	79	83	82	36	37	36	36	39	35	73	72	72	72	72	71
09-07-14	109	108	109	112	110	109	110	107	110	111	108	109	82	81	82	81	80	79	82	82	81	81	82	80	81	81	81	79	81	80	81	80	81	80	83	82	36	37	36	36	39	35	74	72	73	73	73	72
10-07-14	109	108	109	112	109	109	110	107	110	111	107	109	81	81	82	81	80	79	82	82	81	81	82	80	81	81	81	79	81	80	81	80	81	80	83	82	37	37	36	36	39	35	74	72	72	73	72	72
11-07-14	108	108	109	112	109	108	110	107	110	111	107	109	81	81	82	80	80	79	82	82	81	81	82	80	81	81	81	79	81	80	81	80	81	79	83	82	37	38	36	36	39	35	74	72	72	73	72	72
12-07-14	109	108	110	112	110	109	110	108	110	111	108	109	82	81	83	81	81	80	82	83	81	81	82	80	82	81	81	79	81	80	81	81	81	80	84	82	37	38	37	36	39	36	74	73	73	74	73	72
13-07-14	109	108	110	112	110	109	110	108	110	111	108	109	82	81	82	81	81	80	82	82	81	81	82	80	82	81	81	79	81	80	81	80	81	80	84	82	37	38	37	36	39	35	74	73	73	74	73	72
14-07-14	109	108	109	112	109	109	110	107	110	111	107	109	82	81	82	81	80	79	82	82	81	81	82	80	82	81	81	79	81	80	81	80	81	80	83	82	38	38	37	36	39	36	74	73	73	74	73	72
15-07-14	109	107.8	109	112	110	108.6	110	107	110	111	107.4	109	81.6	80.9	82	81	80	79	82	82	81	81	82	80.2	82	81	81	79	81	80.1	81	80	81.2	80	83.4	82	37	38	37	36	39	36	74	73	73	74	73	72
16-07-14	108	106.9	108	111	109	107.7	109.1	106	109	110.2	106.6	108	80.7	80.1	81	80	80	79	81	81	80.2	80	81	79.3	81	80	80	78	80	79.3	80	80	80.4	79	82.6	81	37	38	36	36	39	35	73	72	72	73	72	71
17-07-14	107	106.5	108	111	108	107.3	108.8	106	109	109.8	106.2	108	80.5	79.9	81	80	79	78	81	81	80	80	81	79.2	81	80	80	78	80	79.1	80	79	80.2	79	82.4	81	36	37	36	36	38	35	73	72	72	73	72	71
18-07-14	106	105.5	107	110	107	106.3	107.7	105	108	108.8	105.2	107	79.2	78.6	80	79	78	77	80	80	78.7	79	80	77.8	79	79	79	77	79	77.8	79	78	78.9	78	81.1	80	36	37	36	35	38	34	72	70	71	72	70	70
19-07-14	106	105.3	107	110	107	106.2	107.6	105	107	108.7	105.1	107	79.2	78.6	80	79	78	77	80	80	78.7	79	80	77.8	79	79	79	77	79	77.8	79	78	78.9	78	81.1	80	36	36	35	35	37	34	72	70	71	72	70	70
20-07-14	106	105.1	107	109	107	106.1	107.3	105	107	108.2	104.8	106	78.9	78.3	80	78	78	77	80	80	78.5	78	80	77.6	79	79	78	77	79	77.6	78	78	78.7	77	80.8	80	36	36	35	35	37	34	72	70	70	71	70	70
21-07-14	108	106.7	108	111	109	107.6	109	106	109	110	106.4	108	80.6	79.9	81	80	79	78	81	81	80.1	80	81	79.2	81	80	80	78	80	79.1	80	79	80.2	79	82.4	81	36	37	36	36	38	35	73	72	72	73	72	71
22-07-14	109	107.8	110	112	110	108.9	110.3	108	110	111.2	107.6	109	81.7	81.1	83	81	81	80	82	82	81.2	81	82	80.4	82	81	81	79	81	80.3	81	81	81.4	80	83.6	82	38	39	40	38	40	37	74	73	73	74	73	72
23-07-14	110	108.6	110	113	111	109.5	111	108	111	111.9	108.4	110	82.4	81.9	83	82	81	80	83	83	81.9	82	83	81.1	83	82	82	80	82	81.1	82	81	82.2	81	84.4	83	39	40	38	38	41	37	75	74	74	74	74	73
24-07-14	109	108.1	110	112	110	109	110.5	108	110	111.4	107.9	109	82	81.4	83	81	81	80	83	83	81.4	81	83	80.6	82	81	81	79	82	80.6	81	81	81.7	80	83.9	83	38	39	38	37	40	37	74	73	74	74	73	72
25-07-14	109	108	110	112	110	109	110.5	108	110	111.4	107.8	109	81.9	81.3	83	81	81	80	83	83	81.4	81	83	80.6	82	81	81	79	82	80.5	81	81	81.6	80	83.8	83	38	39	38	37	40	36	74	73	73	74	73	72
26-07-14	109	107.7	109	112	110	108.6	110.1	107	110	111	107.5	109	81.6	81	82	81	80	80	82	82	81.1	81	82	80.3	82	81	81	79	81	80.3	81	80	81.3	80	83.5	82	38	39	37	37	40	36	74	73	73	73	73	72
27-07-14	108	107.3	109	112	109	108.1	109.7	107	109	110.7	107.1	109	81.4	80.8	82	81	80	79	82	82	80.9	81	82	80.1	81	81	81	79	81	80	81	80	81.1	80	83.3	82	38	38	37	37	40	36	74	73	73	73	73	72
28-07-14	108	106.6	108	111	109	107.4	109	106	109	109.9	106.4	108	80.8	80.2	82	80	80	79	82	82	80.3	80	81	79.5	81	80	80	78	81	79.5	80	80	80.5	79	82.7	82	37	38	37	36	39	36	73	72	72	73	72	71
29-07-14	108	106.8	108	111	109	107.7	109.3	106	109	110.2	106.6	108	80.9	80.3	82	80	80	79	82	82	80.4	80	82	79.6	81	80	80	78	81	79.5	80	80	80.6	79	82.8	82	38	38	37	37	39	36	73	72	72	73	72	71
30-07-14	108	107.4	109	112	109	108.3	109.8	107	110	110.7	107.1	109	81.5	80.9	82	81	80	79	82	82	81	81	82	80.1	82	81	81	79	81	80.1	81	80	81.2	80	83.4	82	38	38	37	37	40	36	74	73	73	74	73	72
31-07-14	109	108.1	110	112	110	109	110.6	108	110	111.5	107.9	109	82.2	81.6	83	81	81	80	83	83	81.7	81	83	80.8	82	82	82	80	82	80.8	82	81	81.8	80	84.1	83	38	39	38	37	40	36	74	73	74	74	73	73
01-08-14	109	108.2	110	112	110	109.2	110.6	108	110	111.5	108	110	82	81.4	83	81	81	80	83	83	81.5	81	83	80.7	82	82	81	80	82	80.6	81	81	81.7	80	83.9	83	38	39	37	37	40	36	74	73	74	74	73	72
02-08-14	110	108.5	110	113	110	109.4	110.9	108	111	111.7	108.2	110	82.3	81.7	83	82	81	80	83	83	81.8	82	83	81	82	82	82	80	82	81	82	81	82	81	84.3	83	38	39	38	37	40	37	75	73	74	74	74	73
03-08-14	108	107.3	109	111	109	108.2	109.7	107	109	110.6	107	109	81.4	80.8	82	81	80	79	82	82	80.9	81	82	80.1	82	81	81	79	81	80.1	81	80	81.1	80	83.3	82	38	39	37	37	40	36	74	73	73	73	73	72
04-08-14	109	107.6	109	112	110	108.5	110.1	107	110	110.9	107.4	109	81.4	80.8	82	81	80	79	82	82	80.9	81	82	80	82	81	81	79	81	80	81	80	81.1	80	83.3	82	38	38	37	37	40	36	74	73	73	73	73	72
05-08-14	108	106.7	108	111	109	107.6	109.1	106	109	110	106.5	108	80.9	80.4	82	80	80	79	82	82	80.5	80	82	79.6	81	81	80	78	81	79.6	80	80	80.7	79	82.9	82	38	38	37	37	39	36	73	72	72	73	72	72
06-08-14	108	107.1	109	111	109	108	109.5	107	109	110.4	106.9	108	81	80.4	82	80	80	79	82	82	80.6	80	82	79.7	81	81	80	79	81	79.7	80	80	80.8	79	83	82	38	38	37	37	40	36	74	72	72	73	73	72
07-08-14	109	107.4	109	112	109	108.4	109.9	107	110	110.7	107.2	109	81.5	80.9	82	81	80	79	82	82	81	81	82	80.2	82	81	81	79	81	80.2	81	80	81.3	80	83.4	82	38	39	37	37	40	36	74	73	73	75	73	72
08-08-14	108	107.3	109	112	109	108.2	109.7	107	110	110.6	107.1	109	81.4	80.8	82	81	80	79	82	82	80.9	81	82	80.1	82	81	81	79	81	80.1	81	80	81.1	80	83.3	82	38	38	37	37	40	36	74	73	73	75	73	72
09-08-14	108	107.3	109	112	109	108.2	109.8	107	110	110.6	107.1	109	81.4	80.8	82	81	80	79	82	82	80.9	81	82	80.1	82	81	81	79	81	80.1	81	80	81.1	80	83.3	82	38	38	37	37	40	36	74	73	73	75	73	72
10-08-14	109	107.4	109	112	109	108.4	109.9	107	110	110.7	107.2	109	81.5	80.9	82	81	80	79	82	82	81.1	81	82	80.2	82	81	81	79	81	80.2	81	80	81.3	80	83.4	82	38	39	37	37	40	36	74	73	73	75	73	72
11-08-14	109	108.3	110	113	110	109.3	110.8	108	111	111.6	108.1	110	82.2	81.6	83	82	81	80	83	83	81.7	82	83	80.8	82	82	82	80	82	80.8	82	81	81.9	81	84.1	83	38	39	38	37	40	36	75	73	74	76	74	73

Challenges on Hydro-Electric Systems – Case 3 contd… (Large Hydrogenerators Operate at Continuous Over-Loads)

Temperature-rise in various parts of generator

Parameters	Max Reached	Remarks
Stator Winding Temp. (^{0}C)	112	Acceptable
Stator Core Temp. (^{0}C)	84	Acceptable
Stator Teeth Temp. (^{0}C)	84	Acceptable
Rotor Temp. (^{0}C)	93.23	Acceptable

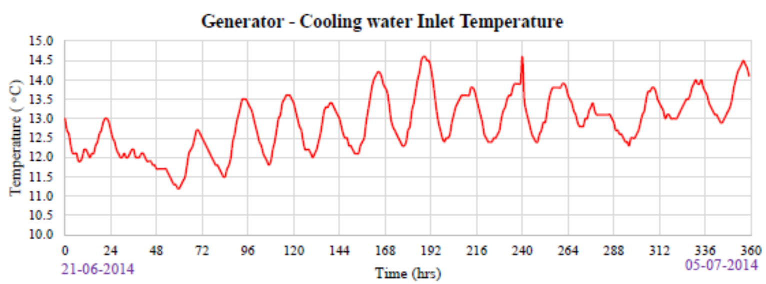
Cooling systems – Need attention

As per agreement:

- surface air coolers shall have sufficient cooling capacity to maintain the temperature of the air leaving the cooler at 35°C or less, with the generator delivering continuous overload capacity at rated voltage and water entering the coolers at 0 to 25°C

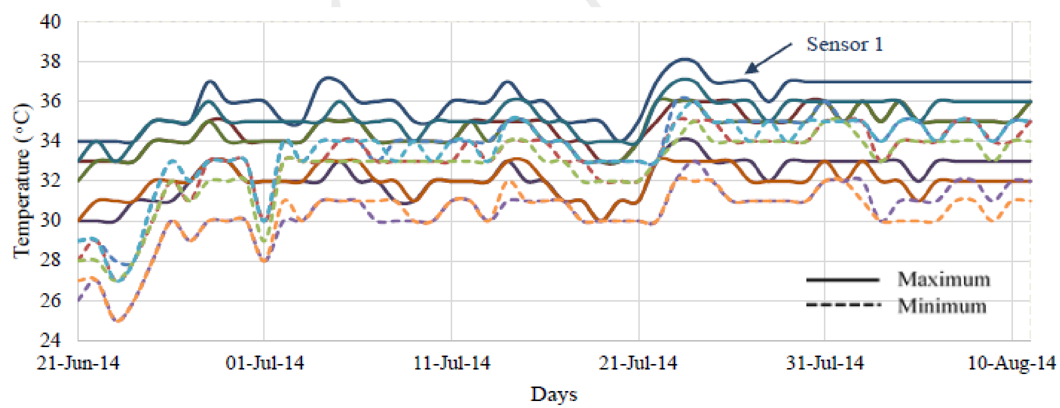
Actual:

- temperature of the air leaving the cooler was reached up to 38°C during the operation of the plant at 120% load provided that the cooling water temperature during this period was observed as 14°C.



Generator parameters and excitation system

Parameters	Max Reached	Remarks
Speed (%)	100.73	Acceptable
Generated Power (MW)	306.92	Acceptable
Reactive Power (MVAr)	89.75	Acceptable
Power factor (Max./Min.)	0.99733 / 0.92947 (Max./Min.)	Acceptable
Generated Voltage (kV)	16.09	Acceptable
Generated Current (kA)	11.29	Acceptable
Field Voltage (V)	199.14	Acceptable
Field Current (A)	2290.14	Acceptable
Excitation Transformer Temperature (°C)	115	Acceptable
Generator Transformer Oil Temperature(°C)	51.39	Acceptable
Generator Transformer Winding Temperature(°C)	62.24	Acceptable



Generator-Cool air inlet temperature

Challenges on Hydro-Electric Systems – Case 4 (Price Variation Cost on Hydrogenerating Equipments)

<u>*Problem Description:*</u>

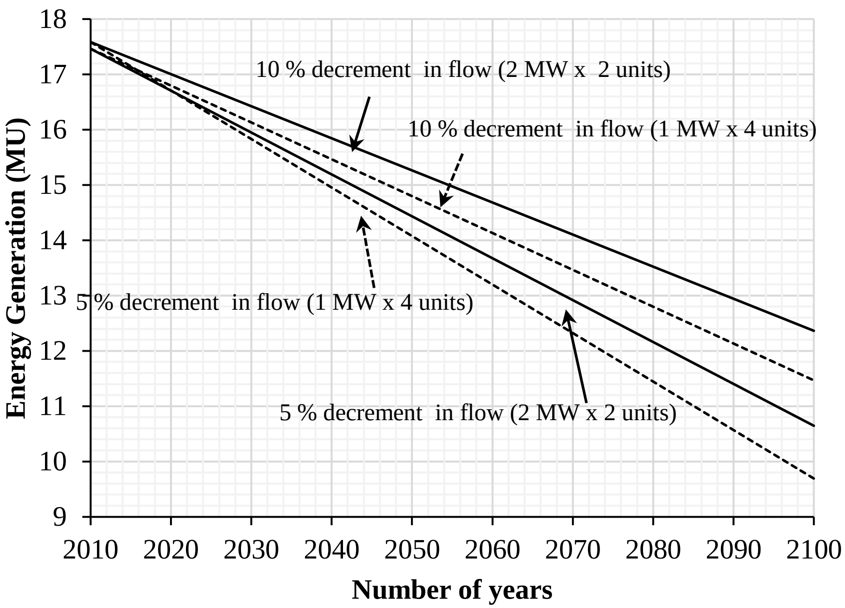
- I planned a project of medium hydropower plant with two units. During construction, I decided to add another unit of same capacity. What are the challenges on commissioning of E&M equipments?

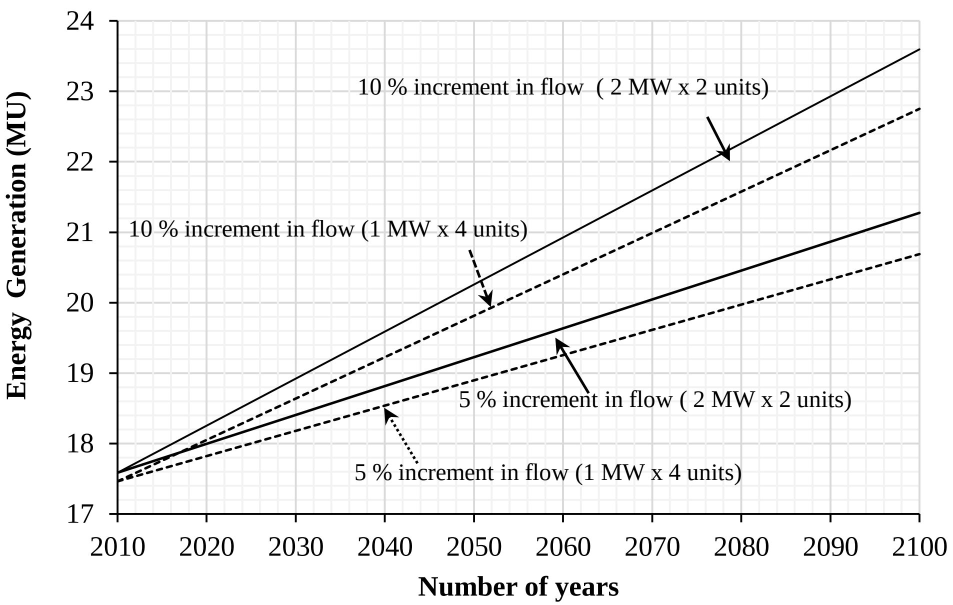
Answer:___________

- Techno Economic Clearance for 2x42 MW by CEA in 1999 at Rs.363.08 Crores
- Project could be started only in October, 2004, after receipt of the Final Forest Clearance
- Revised cost estimation as Rs.671.29 Crores in 2007
- Another Unit of 1x42 MW was added to the Project at a cost of Rs. 114.49 Crores in 2008
- Major floods in 2009 and 2010
- Revision in drawings for Dams, Penstock and Power House etc., the Project had undergone another 2 (two) revision of cost in 2009 (Rs. 965.93 crores) and 2010 (Rs. 1173.13 crores).
- Completion cost Rs. 1286.53 Crores
- Unit 1 and 2 synchronized with grid in 2012 & unit 3 in 2013
- The completion cost of Unit I & II has increased mainly because of payment for delays in supply
- PVC was higher due to (i) delay in finalization of design drawings, (ii) change in design due to addition of an unit, (iii) lack of storage space for the hydro-generating equipments, and (iv) delay in utilization of such equipments due to delay in civil works of power house because of flood.

Myntdu Leska project

Climate Change Impact of SHP





- It is estimated that global warming is increased by 4.3°F to 11.5°F by 2100
- Variable speed technology in hydropower generation has less impacts of climate change

Ongoing Research in Variable Speed Hydro

- Effective utilization of converters [1]
- Hydraulic governor control systems [2]
- Thermal loading [3]
- Cyber security [4]
- Vibration and active power oscillation [5-8]
- Speed Optimization

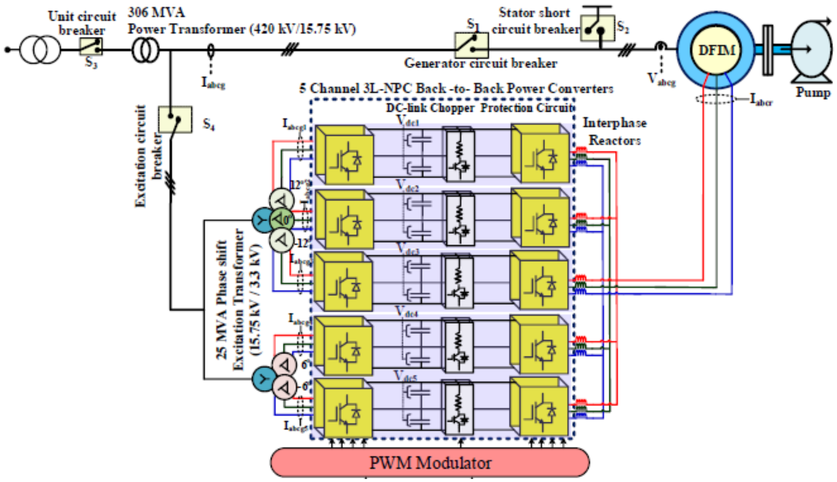


Fig: Electrical diagram of variable speed hydro unit

[1] Karthik D., S. Raghu, Thanga Raj Chelliah, D. Khare "Effective Utilization of Parallel Connected Megawatt Three-Level Back-to-Back Power Converters in Variable Speed Pumped Storage Units," ***IEEE Trans. Industry Applications***, *Vol. 55, No. 6, 2019.*

[2] Rupesh Kumari, Thanga Raj Chelliah, K K Prabhakaran, Intelligent Hydro Turbine Control System for Variable Speed Hydro Generating Unit, **Indian Patent** (filed in April 2022 through iHub Divyasampark, IIT Roorkee- Appl. No. 202211023178).

[3] KarthikDesingu, Raghu Selvaraj, Thanga Raj Chelliah, **"**Control of Reactive Power for Stabilized Junction Temperature in Power Electronic Devices Serving to a 250 MW Asynchronous Hydro-Generating Unit" ***IEEE Trans. Industry Applications***, *Vol. 55, No. 6, 2019.*

[4] Chandrasekar S, Mayur, Thanga Raj Chelliah, A system and method for the detection of cyberattack on automatic generation control (AGC) signal of electric power plant, **Indian Patent** (filed in Sept. 2022 through iHub Divyasampark, IIT Roorkee, Appl. No. 202211052352).

*[5] Ritu Tiwari, T R Chelliah "*Design Improvement and Tuning of Excitation System ST5B with PSS3B and Coordinated OEL in Hydropower Plant", in ***IEEE Transactions on Industry Applications,*** vol. 58, no. 5, pp. 5895-5907, 2022.

[6] Javed Ali, Thanga Raj Chelliah and Pramod Agarwal, "Estimation of Stator Vibration in DFIM Under Various Types of Rotor Excitation", in ***IEEE Trans. Industry Applications,*** *early access (https://ieeexplore.ieee.org/document/10106443).*

[7] Vijay Mohale, T R Chelliah, Yogesh Hote "Analysis and Damping of Sub-Synchronous Oscillations in a 250 MW DFIM Hydro Unit Connected to Series Compensated 765 kV Transmission Lines", in ***IEEE Trans. Industry Applications***, vol. 59, no. 2, pp. 5895-5907, 2023.

[8] Vijay M, J. Ali, S. Sonandkar, T R Chelliah, Y. Hote, A control system and method to dampen SSO in variable speed pumped storage units connected with extra high voltage transmission lines, **Indian Patent** (filed in Dec. 2022 through iHub Divyasampark, IIT Roorkee, Appl. No. 202211069377)

Conclusions and Future Scopes

- The power electronics technology plays an immense role in the development of hydroelectric power generation. Its contributions in hydropower and pumped storage schemes will continue in the future.
- Var Speed: The efficiency of the plant will be more with variable speed technology for all head. The resource can be utilized up to its maximum extent.
- Pump mode: In India, availability of surplus power remains for very less time simultaneously it does not remains constant. Hence part load behavior of the pump is a very important point of concern.
- Challenges on hydro-electric systems were discussed through case studies.

Future Scopes

- Redundancy in VarSpeed hydro
- Flywheel energy storage to penetrate large amount of RE into grid
- Renovation and modernization of existing hydro plants
- Measurement of DC component in stator (ac) winding

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Government of India

सत्यमेव जयते
Ministry of Electronics and Information Technology
Government of India

OPAL-RT TECHNOLOGIES

एसजेवीएन
SJVN

References

Report on "Analysis of dynamic performance of variable speed hydroelectric plants under grid disturbances" to THDC India Ltd (2017).

Report on "Cost verification of 3X42 MW Myntdu Leshka Hydroelectric Project (MLHEP)" to Meghalaya Power Generation Corporation Ltd. (2014).

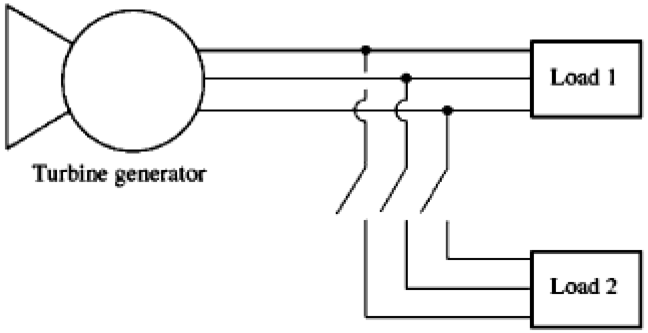
Report on "Evaluation and Checking of Adequacy of Project Components for 20% Overload Condition of Karcham-Wangtoo Hydroelectric Project) to Jaiprakash Power Ventures Limited (JPVL) (2015).

Anto Joseph and Thanga Raj Chelliah, "A Review of Power Electronic Converters for Variable Speed Pumped Storage Plants: Configurations, Operational Challenges and Future scopes", IEEE Journal of Emerging and Selected Topics in Power Electronics May 2017.

Anto Joseph, Karthik Desingu, R.R. Semwal, T. R. Chelliah, and Deepak Khare "Dynamic Performance of Pumping Mode of 250 MW Variable Speed HydroGenerating Unit Subjected to Power and Control Circuit Faults," IEEE Transactions on Energy Conversion, August 2017, doi: 10.1109/TEC.2017.2739132.

Karthik Desingu, T. R. Chelliah and Deepak Khare," Sustainable Operation of Small Hydropower Schemes in Changing Climatic Conditions," in proc 9th IEEE International Conference on Asia-Pacific Power and Energy Engineering, Bangalore, November 2017

tutorial: syn. gen. operating alone



whether speed governor system employed to mini/micro hydropower plant is economical or not?

Figure shows a generator supplying a load. A second load is to be connected in parallel with the first one. The generator has a no-load frequency of 51.0 Hz and a slope S_p of I MW/Hz. Load 1consumes a real power of 1000 kW at 0.8 PF lagging, while load 2 consumes a real power of 800 kW at 0.707 PF lagging.

(a) Before the switch is closed, what is the operating frequency of the system?
(b) After load 2 is connected, what is the operating frequency of the system?
(c) After load 2 is connected, what action could an operator take to restore the system frequency to 50 Hz?

Ans: (a) 50Hz, (b) 49.2 Hz,

(c) the operator should increase the governor no-load set points by 0.8 Hz, to 51.8 Hz. This action will restore the system frequency to 50 Hz.

Thank you for your attention