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Part load operation in M.D hydro power plant unit two

ALI AHMED ALI ADAM
Lecturer
Mechanical Engineering Department
University Abdulatif Alhamad Merowe, Sudan
TAWFIG AHMED GAMAL ELDIN ABDALRHMAN
Associate Professor
Mechanical Engineering Department, University of Sudan, Sudan
ABDALLAH MOKHTAR MOHAMMED ABDALLAH
Assistant Professor
Mechanical Engineering Department, University of Sudan, Sudan

Abstract:

*The flow in the Francis turbines draft tube cone operate at partial discharge is a complex hydrodynamic phenomenon. And has special attention because unacceptable source and resulting pressure pulsation, power fluctuation and putting the plant at risk [4]. The head and discharge values are two main factors that affects vortex structure and the performance of the draft tube then hydraulic system[6] . This paper presents the part load operation conditions in the draft tube cone at three deferent heads (cases) in M. D. Hydro power plant. The study is undertaken for operating conditions parameters corresponding to high part load 0.9*Q_{BEP} *to low part load 0.5* Q_{BEP}*. The discharge coefficients is used to predict specific speed and swirl number, The minimum swirl number is 0.11 at BEP case (A) and maximum is 1.05 at 0.5* Q_{BEP} *when the head 33 m case(c). It is shown that the rise in the pressure pulsation due to swirl increase.*

Key words: draft tube, Francis , part load; swirl number; vortex rope

1. INTRODUCTION

The variable demand of the energy market forces that hydraulic turbine to work at different loads, which includes the regimes far from Best Efficiency Point (BEP). When fixed-pitch blades runners(Francis turbine) running at part load the ideal design flow is disrupted and changed [10] . On other hand , the discharge downstream the runner and at inlet of draft tube cone that can create serious operating challenges associated with partial operations ($Q > Q_{BEp}$) like vortex ropes and swirling flow which causes efficiency reduction, severe pressure pulsation, and even structural vibration[8]. which could prevent the whole hydro power plant from operating safely under operation conditions[1] [7] .

The experimental studies of the flow in the draft tube cone large research project FLINDT (Flow Investigation in Draft Tubes) with its relatively large amount of experimental data base describing a wide range of operating points of the Francis turbine was conducted at EPFL Lausanne []. Also Using Particle Image Velocimetry Measurements (PIV) in the draft tube cone of the Francis turbine model in order to cover lack of experimental data for the draft tube swirling flow with the vortex rope [6].

The present working is aim to study the swirl vortex at partial operation conditions between ranges 0.9 Q_{BEp} to 0.5 Q_{BEp} in M.D hydro power plant unit two in three different heads (cases) to assess the operation regimes at part load in M. D Plant

2. M. D. Hydro power operation zone and test case

In figures (1) and (2) below showed the zone of operation which characteristics by operation without vortex , at full load operation the flow under given conditions flow rate is less than

Q_{min} . Q_{BEP} the designed according to operation flow angle open see table (1).

The test case corresponds to a medium specific speed Francis turbine with dimensionless specific speed (v).The distributor consists of 24 stay vanes and 24 guide vanes whilst the runner has 13 blades with the reference diameter 6 (m)

Table (1) flow condition

Case	H (m)	$Q_{max.}$ (m^3/s)	Q_{BEp} (m^3/s)	Q_{min} (m^3/s)
A	45	275	262.5	250
B	35	266.07	255.355	244.64
C	33	264.2827	254.3914	244.5

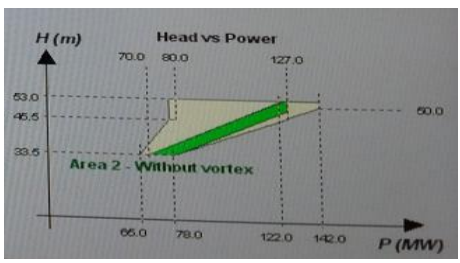

Figure (1) operation without vortex zone

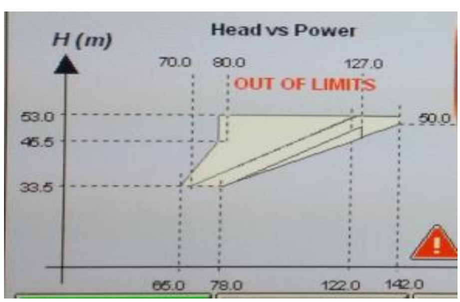

Figure (2) operation with vortex none

3. Runner outlet flow at part load

The velocity exit from the runner depends on the operating conditions of the turbine. Because the blade angle in Francis turbines is fixed (22 ̊), the relative angle between U and W at the runner outlet is practically constant for every operating point. The flow entering the draft tube rotates in the same direction as the runner. Fig. (3) shows the outlet velocity triangle for a runner at part load .[2][11][10]

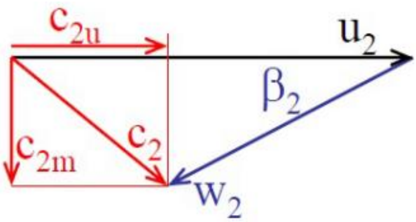

Figure (3) Velocity triangle for the outlet at part load.[2][11][5]

3.1. Draft Tube vortex rope formation

While the turbine discharge is decreased a high residual swirl (as a result of the mismatch between the swirl generated by the guide vanes and the angular momentum extracted by the turbine runner) enters the draft tube inlet. [8]Experimental, numerical, and analytical investigations have been carried out for more than fifty years to understand and to predict the vortex rope formation. [6]

4. REDUCED TERM

The unit quantities give the discharge(Q_{11}), speed (n_{11})and power(P_{11}) for a particular turbine under a head of 1m depending on guide vanes opening (gamma) . The reduced data required to build the Francis turbine Hydro HillChart for designed condition [3]. The parameter used in reduced term discharge (Q) , diameter(D),head (H),speed (n) and power (P).

The reduces terms Q_{11} and P_{11} in three heads are decrease when part load flow increase ,but the terms are (Q_{11} , P_{11}) are increase when the head decrease . The term n_{11} is constant when part load increase but increase when the head decrease ,at case B and C n_{11}> N see tables see tables (2) and (3)

Table (2) reduced term Case A

Ga. (Deg.)	Q (m^3/s)	Q_{11} (L/s)	n_{11} (r.p.m)	P_{11} (KW)	P (MW)	**ηp** %
15.9	131.3	547.1	89.42	3.8	40.4	70.0
18.7	157.5	655.7	89.42	5.2	55.2	80.4
21.7	183.8	772.4	89.42	6.6	68.8	87.7
24.5	210	874.4	89.42	7.7	83.4	90.3
28.2	236.3	987.3	89.42	8.9	93.7	92.3
29.7	250	1036.4	89.42	9.4	102.2	93.4
31.3	262.5	1087.2	89.42	10.0	108.8	94.6
33.2	275	1139.4	89.42	10.6	114.3	95.1

Table (3) reduced term Case B

Ga. (Deg.)	Q (m^3/s)	Q_{11} (L/s)	n_{11} (r.p.m)	P_{11} (KW)	P (MW)	**ηp** %
17.7	127.7	599.4	101.4	3.6	27.22	62.4
21.2	153.2	716.9	101.1	5.1	38.76	73.6
24.0	178.7	839.0	101.4	6.7	50.35	82.2
27.7	204.3	959.4	101.4	8.1	60.35	86.6
31.2	229.8	1071.2	101.4	9.3	71.79	89.5
35.0	244.6	1187.4	101.4	10.9	81.36	92.9
35.8	255.4	1209.9	101.4	11.1	82.93	93.6
37.4	266.1	1248.6	101.4	11.4	84.99	93.5

5. Effect of the partial load in factors

The speed factor is depend on head only and it decrease when head increase show table (5) . The discharge factor decrease when part load flow increase , and increase when head decrease show table (6). The power factor decrease when part load flow increase and decrease when head decrease show table (7)

Table (5). Speed factor for three cases

cases	H_m	nD	$\sqrt{\mathbf{E}}$	60 $\sqrt{\mathbf{E}}$	N_{ED}
C	33	600	17.989	1079.312	0.556
B	35	600	18.526	1111.537	0.540
A	45	600	21.006	1260.364	0.476

Table (6) discharge factor

Part Load	Case A			Case B			Case C		
	Ga.(deg)	Q(m^3/s)	Q_{ED}	Ga.(deg)	Q(m^3/s)	Q_{ED}	Ga.(deg)	Q(m^3/s)	Q_{ED}
$0.5Q_{BEp}$	15.9	131.3	0.17	17.8	127.7	0.20	18.3	127.2	0.20
$0.6Q_{BEp}$	18.7	157.5	0.21	21.3	153.2	0.23	22	152.6	0.24
$0.7Q_{BEp}$	21.7	183.75	0.24	24.0	178.7	0.27	25.1	178.1	0.27
$0.8Q_{BEp}$	24.5	210	0.28	27.8	204.3	0.31	28.4	203.5	0.31
$0.9Q_{BEp}$	28.2	236.25	0.31	31.2	229.8	0.34	32.7	229	0.35
Q_{min}	29.7	250	0.33	35.0	244.6	0.37	35	244.5	0.38
Q_{BEp}	31.3	262.5	0.35	35.8	255.4	0.38	36.6	254.4	0.392
$Q_{max.}$	33.2	275	0.36	37.4	266.1	0.4	33.2	264.3	0.76

Table (7) power factor

Part load	Case A			Case B			Case C		
	Ga.(deg)	P(mw)	P_{ed}	Ga.(deg)	P(mw)	P_{ed}	Ga.(deg)	P(mw)	P_{ed}
$0.5Q_{BEp}$	15.9	40.35	0.121	17.8	27.22	0.119	18.3	24.39	0.117
$0.6Q_{BEp}$	18.7	55.17	0.166	21.3	38.76	0.169	22	35.06	0.168
$0.7Q_{BEp}$	21.7	68.79	0.207	24.0	50.35	0.220	25.1	45.66	0.218
$0.8Q_{BEp}$	24.5	83.36	0.25	27.8	60.36	0.264	28.4	56.26	0.269
$0.9Q_{BEp}$	28.2	93.67	0.281	31.2	71.79	0.314	32.7	64.8	0.310
Q_{min}	29.7	102.20	0.307	35.0	81.36	0.356	35	71.70	0.343
Q_{BEp}	31.3	108.83	0.327	35.8	82.93	0.363	36.6	75.72	0.362
$Q_{max.}$	33.2	114.28	0.343	37.4	85.00	0.343	33.2	78.63	0.376

6. The the head(ψ) coefficients

The energy coefficient increase with head increase table (8)

Table (8) head(ψ) coefficients

	H_m	2gH	$(\omega D/2)^2$	Psi Ψ
C	33	647.13	986.95	0.65
B	35	686.35	986.95	0.69
A	45	882.45	986.95	0.89

7. The discharge coefficients at part load conditions (φ)

The discharge coefficient at part load decrease when part load flow increase and decrease when head decrease show table (9). The discharge coefficient at $0.9Q_{BEp}$ in tow cases are the same operating point of the FLINDT Francis turbine at discharge coefficient $(\varphi) =$ 0.26[8].

7.1 specific discharge coefficient (φ^*)

Discharge coefficient divided by the discharge coefficient at φ BEP value($\varphi^* = \phi/\phi_{BEp}$) show table (10)

Table (9) discharge coefficient (φ)

Part load	Case A			Case B			Case C		
	Ga.(deg)	Q(m^3/s)	ϕ	Ga.(deg)	Q(m^3/s)	ϕ	Ga.(deg)	Q(m^3/s)	ϕ
$0.5Q_{BEp}$	15.9	131.3	0.148	17.8	127.7	0.144	18.3	127.2	0.143
$0.6Q_{BEp}$	18.7	157.5	0.177	21.3	153.2	0.172	22	152.6	0.172
$0.7Q_{BEp}$	21.7	183.75	0.207	24.0	178.7	0.201	25.1	178.1	0.200
$0.8Q_{BEp}$	24.5	210	0.236	27.8	204.3	0.230	28.4	203.5	0.229
$0.9Q_{BEp}$	28.2	236.25	0.266	31.2	229.8	0.259	32.7	229	0.258
Q_{min}	29.7	250	0.281	35.0	244.6	0.275	35	244.5	0.275
Q_{BEp}	31.3	262.5	0.296	35.8	255.4	0.287	36.6	254.4	0.286
$Q_{max.}$	33.2	275	0.310	37.4	266.1	0.300	33.2	264.3	0.298

Table (10) specific discharge coefficient φ*

Part load	Case A			Case B			Case C		
	Ga.(deg)	ϕ	φ*	Ga.(deg)	. ϕ	φ*	Ga.(deg)	ϕ	φ*
$0.5Q_{BEp}$	15.9	0.148	0.5	17.8	0.144	0.5	18.3	0.143	0.5
$0.6Q_{BEp}$	18.7	0.177	0.6	21.3	0.172	0.6	22	0.172	0.6
$0.7Q_{BEp}$	21.7	0.207	0.7	24.0	0.201	0.7	25.1	0.200	0.7
$0.8Q_{BEp}$	24.5	0.236	0.8	27.8	0.230	0.8	28.4	0.229	0.8
$0.9Q_{BEp}$	28.2	0.266	0.9	31.2	0.259	0.9	32.7	0.258	0.9
Q_{min}	29.7	0.281	0.95	35.0	0.275	0.96	35	0.275	0.96
Q_{BEp}	31.3	0.296	1	35.8	0.287	1	36.6	0.286	1
$Q_{max.}$	33.2	0.310	1.05	37.4	0.300	1.04	33.2	0.298	1.04

Since operation is usually done at a known constant runner speed, it is convenient for hydraulic performance purposes to use dimensionless coefficients for the discharge and net head.

The swirling flow by specific discharge coefficient (φ*) show in table (11) equal zero at BEP, positive value at part load and negative value at full load.

Table (11) The swirling flow by specific discharge coefficient (φ*)

Part load	Case A			Case B			Case C		
	Ga.(deg)	φ^*	$V_{2\Theta}$(m/s)	Ga.(deg)	φ^*	$V_{2\Theta}$(m/s)	Ga.(deg)	φ^*	$V_{2\Theta}$(m/s)
$0.5Q_{BEp}$	15.9	0.5	15.71	17.8	0.5	15.70	18.3	0.5	15.7
$0.6Q_{BEp}$	18.7	0.6	12.57	21.3	0.6	12.57	22	0.6	12.57
$0.7Q_{BEp}$	21.7	0.7	9.42	24.0	0.7	9.42	25.1	0.7	9.42
$0.8Q_{BEp}$	24.5	0.8	6.28	27.8	0.8	6.28	28.4	0.8	6.28
$0.9Q_{BEp}$	28.2	0.9	3.14	31.2	0.9	3.14	32.7	0.9	3.14
Q_{min}	29.7	0.95	1.50	35.0	0.96	1.32	35	0.96	1.22
Q_{BEp}	31.3	1	0	35.8	1	0	36.6	1	0
$Q_{max.}$	33.2	1.05	-1.50	37.4	1.04	-1.32	33.2	1.04	-1.22

Table (12) specific speed (v_s)

	Case A		Case B		Case C	
	Ga.(deg)	v_s	Ga.(deg)	v_s	Ga.(deg)	v_s
$0.5Q_{BEp}$	15.9	0.42	17.8	0.49	18.3	0.52
$0.6Q_{BEp}$	18.7	0.46	21.3	0.54	22	0.57
$0.7Q_{BEp}$	21.7	0.501	24.0	0.59	25.1	0.62
$0.8Q_{BEp}$	24.5	0.53	27.8	0.63	28.4	0.66
$0.9Q_{BEp}$	28.2	0.569	31.2	0.67	32.7	0.70
Q_{min}	29.7	0.58	35.0	0.70	35	0.731
Q_{BEp}	31.3	0.59	35.8	0.71	36.6	0.74
$Q_{max.}$	33.2	0.61	37.4	0.63	33.2	0.76

7. Swirling Flow in the Draft Tube

Experience has shown that the main factor for triggering the vortex breakdown is the dimensionless swirl number is used to describe the amount of [3][9].

Table (13) swirl number.

	Case (A)	Case (B)	Case (C)
$0.5Q_{BEp}$	0.91	1.03	1.05
$0.6Q_{BEp}$	0.58	0.66	0.68
$0.7Q_{BEp}$	0.39	0.48	0.49
$0.8Q_{BEp}$	0.27	0.34	0.36
$0.9Q_{BEp}$	0.18	0.23	0.25
Q_{min}	0.14	0.11	0.20
Q_{BEp}	0.11	0.14	0.17
$Q_{max.}$	0.08	0.13	0.15

Swirl present in the flow. This swirl number (s) is defined as the ratio of angular flux of moment-of-momentum to the axial flux of axial momentum times the inlet radius[10] A suitable analytical representation of the swirling flow has been developed taking the discharge coefficient as independent variable. In case A the swirl number is 0.11 at BEP and 0.91 at $0.5Q_{BEp}$, in case C the swirl number is 0.17 at BEP and 1.05 at $0.5Q_{BEp}$. The swirl number increase when part load increase also increases when head decrease table (13).

$$S = \frac{\text{Angular momentum}}{\text{Axial momentum}} \ [6]$$

8. The Vortex Rope Frequency

Frequencies that are expected in the case study (Francis turbine unit two) can be calculated with information that the turbine is equipped with 24 guide vanes and 13 runner blades[9]. The expected frequencies to be found at M . D .hydro power plant are presented in Table (14) below

The dominating pressure pulsation amplitudes are assumed to be in the range of 0.42 – 0.56 Hz.

f_b is guide blades

fg is guide vanes

fr is Rheingans frequency at part load

F_v vortex frequency

Table (14)

1	F_n=n/60	1.6667 Hz
2	$f_b = F_n$*b	21 Hz
3	$F_g = F_n$*g	40 Hz
4	fr	0.46≤ fr ≤ 0.56 Hz
5	fv / fn	0.278 Hz

9. Pressure pulsation

The swirling flow developing in Francis turbine draft tube under part load operation leads to pressure pulsation usually in the range of 0.2 to 0.4 times the runner rotational frequency resulting from the so- called vortex breakdown according toW.J. Rheingans [9].

When the flow downstream the runner at BEP, it does not have a tangential velocity (no swirl), significance the flow is perpendicular to the shaft axis. [11]At operation partial load , the direction of the exit flow changes and generate a tangential velocity component. The pressure internal the vortex is lower than the pressure in the surroundings, with generate pulsations every time the vortex passes a specific point on the wall table (15) the pressure pulsation (ΔH/H%)

part load increase in three cases after $0.9Q_{BEp}$ and hard in case (C) low head retched over 34 at $0.5Q_{BEp}$. The amplitude becomes dominant at part load.

Table (15) Pressure pulsation

	Case A		Case B		Case C	
	ΔH (mwc)	ΔH/H%	ΔH (mwc)	ΔH/H%	ΔH (mwc)	ΔH/H%
$0.5Q_{BEp}$	11.32	25.16	11.31	32.32	11.32	34.31
$0.6Q_{BEp}$	7.25	16.10	7.25	20.70	7.25	21.96
$0.7Q_{BEp}$	4.08	9.06	4.08	11.65	4.08	12.35
$0.8Q_{BEp}$	1.81	4.03	1.81	5.18	1.81	5.49
$0.9Q_{BEp}$	0.45	1.01	0.45	1.29	0.45	1.37
Q_{min}	0.10	0.23	0.08	0.23	0.07	0.21
Q_{BEp}	0	0	0	0	0	0
$Q_{max.}$	0.10	0.23	0.08	0.23	0.07	0.21

10 .Equations used

The equations used. [4][6][9][13]

$$Q_{11} = \frac{Q}{D^2 H^{0.5}} \quad (1)$$

$$n_{11} = \frac{nD}{H^{0.5}} \quad (2)$$

$$P_{11} = \frac{p}{D^2 H^{1.5}} \quad (3)$$

$$N_{ED} = \frac{nD}{60\sqrt{E}} \quad (4)$$

$$Q_{ED} = \frac{Q}{D^2\sqrt{E}} \quad (5)$$

$$P_{ED} = \frac{p}{\rho D^2 E^{1.5}} \quad (6)$$

$$\text{Psi } \Psi = \frac{2E}{(\omega D/2)^2} \quad (7)$$

$$\omega = \frac{2\pi n}{60} \quad (8)$$

$$\text{Phi } \phi = \frac{Q_1}{\pi\omega(D/2)^3} \quad (9)$$

$$v_s = \omega \frac{\left(\frac{Q}{\pi}\right)^{\frac{1}{2}}}{(2gH)^{\frac{3}{4}}} = \frac{\varphi^{\frac{1}{2}}}{\psi^{\frac{3}{4}}} \quad (10)$$

$$U_2 = (\pi D_2 n)/60 \quad (11)$$

$$V_{2\Theta} = U_2 (1 - \phi/\phi_{BEP}) \quad (12)$$

$$Fn/3.6 \le fr \le Fn/3 \quad Hz \quad [13]$$

$$\Delta H = k(V^2_{2\Theta})/2g. \quad (14)$$

11. Conclusions

1-New reduced terms discharge(Q_{11}), speed (n_{11}) and power(P_{11}) were predicted for reduced terms of turbine under unit head gives us new turbine at part load condition.

2-The speed factor depend only on head change and inverse relation . The discharge and power factors are inverse with head and part load .All factors are new specification for hill chart operation .

3-Using the discharge coefficient ϕ, ϕ_{BEP} and transport velocity U_2 , together to find swirl velocity $V_{2\Theta}$ in different regimes of operations.

4-The vortex frequency at natural operation in M.D. power plant is 0.46 but in [9] between 0.2 to 0.4

5-The pressure pulsation ($\Delta H/H\%$) part load increase in three cases after $0.9Q_{BEp}$ and very hard in case (C) low head retched over 34 at $0.5Q_{BEp}$

Nomenclature

E = turbine specific hydraulic energy,[J/kg]
H = head [m]
Q_{BEP} = discharge value at the best efficiency operating point [m^3 / s]
Q_{11} = reduced discharge [L/s]
Q_{Ed}= Discharge factor
N = runner speed [min^{-1}]
N_{11} = reduced speed
N_{ED} = speed factpr
P = generated power [MW]
P11 = reduced power [KW]
P_{ED} = power factor
V_s= turbine specific speed
.ω = Angular speed
f = frequency [Hz]
f_n =runner rotation frequency [Hz]
Ψ= specific energy coefficient
.ϕ = discharge coefficient
.ϕ^* = specific energy coefficient divided by the BEP value

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