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TITLE:	SPECIFICATION OF EDP FUNCTIONS: "COMPUTE MSV - TURBINE EFFICIENCY (S6)"
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CONTENTS

PREFACE

This document contains a description of the maintenance function «Compute MSV - Turbine efficiency» (S6).

1. OBJECTIVE OF FUNCTION

The function objective is to assess the loss in efficiency and/or power of the machine resulting from wear, through a test programme including several operating points within the normal working range. In addition, it may be useful for other purposes, such as to assess the change in efficiency after repair or modification and due to the onset of cavitation resulting from a change of suction specific potential energy and/or specific hydraulic energy.

2. FUNCTION ENVIRONMENT

The function is a part of the supervision/monitoring maintenance domain.

Based on process measurements, the function calculates, if needed, the actual value of the efficiency for the specified operating points. Also performs the estimation of the expected efficiency for the same operating conditions from the equipment technical data, using affinity laws.

The function is activated by a maintenance operator and the sequence of requests and responses necessary to utilise the function is the following:

Event	Request/Response (RQ/RS)	From	To
Perform efficiency calculation	RQ	MO	CO or Function
Acknowledge	RS	CO or Function	MO
Specify operating points	RQ	CO or Function	MO
Operating points specification: – turbine (example): 5/10, 6/10, 7/10, 8/10, 9/10 and/or 10/10 of maximum guide vane opening – pump (for a pump-turbine)	RS	MO	CO or Function

Event	Request/Response (RQ/RS)	From	To
Present results: – turbine (for each operating point): guide vane opening (α), headwater level (z_3), tailrace level (z_4), head ($H = E / \overline{g}$), flow (Q), power (P), efficiency (η) – pump: headwater level, tailrace level, head, flow, power, efficiency	RS	CO	MO
Conversion of power and flow for each operating point to the same head.	RQ	MO	Function
Perform efficiency estimation for the same head	RQ	MO	Function
Calculate actual weighted average efficiency Calculate expected weighted average efficiency Calculate efficiency change	RQ	MO	Function
Present results: – turbine: • table 1 (actual efficiency for the specified operating points): α, z_3, z_4, H, Q, P, H_{sp}, Q_{sp}, P_{sp}, η • table 2 (expected efficiency for the specified operating points): α, H_{sp}, Q_{sp}, P_{sp}, η • graphic 1: η (actual and expected) plotted against P_{sp} • graphic 2: P_{sp} (actual and expected) plotted against H_{sp} – pump: • tables 1 and 2 (actual and expected values respectively) • graphics: actual value and expected curve of Q, P, and η plotted against H	RS	Function	MO

Event	Request/Response (RQ/RS)	From	To
Present results (cont.): – actual weighted average efficiency – expected weighted average efficiency – efficiency change			

3. INPUT DATA DEFINITION

Acquired data (from event communication flow):

1 guide vane opening (α), %
2 headwater level (z_3), m
3 tailrace level (z_4 or $z_{2"}$), m
4 upstream (high pressure section) gauge pressure (p_1), Pa
5 downstream (low pressure section) gauge pressure (p_2), Pa
6 water flow (Q), m^3/s
7 active power (P_a), kW
8 reactive power (P_r), kvar
9 water temperature (Θ), K
10 cooling water flow (q), m^3/s
11 air temperature at machine reference level (Θ_a), K
12 ambient pressure at machine reference level (P_{amb}), Pa

Calculated data (from event communication flow):

1 turbine efficiency η (when calculated by control system), %

Configured data (equipment technical data):

Plant data

1 latitude (ϕ), (º)

Hydraulic machine data

1 rotational speed (n), s^{-1}
2 machine reference diameter (D), m
3 machine reference level (z_r), m
4 upstream section elevation (z_1), m

5 difference of elevation between machine upstream section level and upstream instrument level (Z_1), m

6 downstream section elevation (z_2 or $z_{2'}$), m

7 difference of elevation between machine downstream section level and downstream instrument level (Z_2), m

8 upstream section area (A_1), m^2

9 downstream section area (A_2 or $A_{2'}$), m^2

10 turbine characteristics:

guide vane opening α_1

head ($H = E / \bar{g}$), m	H_1	...	H_j	...	H_m
flow (Q), m^3/s					
power (P), kW					
efficiency (η), %					
unit speed (n_{11})					
unit flow (Q_{11})					
unit power (P_{11})					
weighting factor (w)					

...

guide vane opening α_i

...

guide vane opening α_n

11 pump characteristics

head ($H = E / \bar{g}$), m	H_1	...	H_j	...	H
flow (Q), m^3/s					
power (P), kW					
efficiency (η), %					
unit speed (n_{11})					
unit flow (Q_{11})					
unit power (P_{11})					
weighting factor (w)					

Electrical machine data

1 mechanical and electric losses (P_b), kW

power factor $\cos\varphi = 1{,}0$

load, %	100	75	50	25
active power (P), kW				
load losses (75 ^{o} C),kW iron losses, kW mechanical losses (including windage losses), kW				
total losses(P_b), kW				

power factor $\cos\varphi =$ rated value

load, %	100	75	50	25
active power (P), kW				
load losses (75 ^{o} C),kW iron losses, kW mechanical losses (including windage losses), kW				
total losses(P_b), kW				

2 thrust bearing losses due to electrical machine (P_c), kW
3 flywheel losses (P_d), kW
4 power supplied to any directly driven auxiliary machine (P_e), kW

Tuning data:

1 number of measurements taken during a run
2 time interval between measurements, s

4. OUTPUT DATA DEFINITION

Output from function:

1 turbine efficiency:

table 1 (actual efficiency for the specified operating points):

guide vane opening (α), %	α_1	...	α_i	...	α_n
headwater level (z_3), m					
tailrace level (z_4), m					
head ($H = E / \overline{g}$), m					
flow (Q), m^3/s					
power (P), kW					
head ($H_{sp} = E_{sp} / \overline{g}$), m					
flow (Q_{sp}), m^3/s					
power (P_{sp}), kW					
efficiency (η), %					

(shaded) data to be stored

table 2 (expected efficiency for the specified operating points):

guide vane opening (α), %	α_1	...	α	...	α_n
guide vane opening (α), %					
head ($H_{sp} = E_{sp} / \overline{g}$), m					
flow (Q_{sp}), m^3/s					
power (P_{sp}), kW					
efficiency (η_{sp}), %					

graphic 1: η (actual and expected) plotted against P_{sp}

graphic 2: P_{sp} (actual and expected) plotted against H_{sp}

2 pump efficiency:

table 1 (actual efficiency):

headwater level (z_3), m	
tailrace level (z_4), m	
head ($H = E / \overline{g}$), m	
flow (Q), m^3/s	
power (P), kW	
efficiency (η), %	

data to be stored

table 2 (expected efficiency):

head ($H = E / \overline{g}$), m	
flow (Q), m^3/s	
power (P), kW	
efficiency (η), %	

graphic 1: actual value and expected curve of Q plotted against H

graphic 2: actual value and expected curve of P plotted against H

graphic 3: actual value and expected curve of η plotted against H

2 actual weighted average efficiency, %

turbine efficiency:

guide vane opening (α), %					
weighting factor (w)					
efficiency (η), %					
weighted average efficiency (η_w), %					

3 expected weighted average efficiency, %

4 efficiency change, %

turbine efficiency:

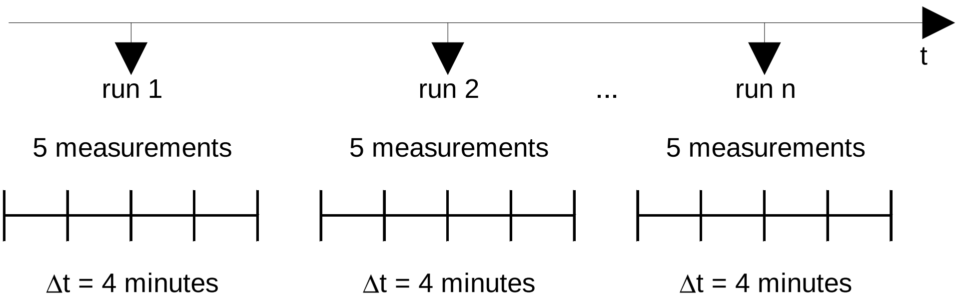
guide vane opening (α), %					
efficiency change($\Delta\eta$), %					
average efficiency change ($\Delta\eta_w$), %					

5. DYNAMIC BEHAVIOUR

The function is activated on maintenance operator request (periodically or after a machine repair or modification).

Measurements required to determinate the machine efficiency must be taken only when steady state conditions prevail and at regular intervals. The number of measurements taken during a run must be at least five and the time intervals between them of around 4 minutes (a run comprises the measurements sufficient to calculate the machine efficiency at one operating condition).

The following figure shows an example of a machine efficiency test schedule:



6. DATA PROCESSING (ALGORITHM)

The function aims at comparing the actual value of hydraulic machine efficiency with the expected one. This involves the evaluation of specific hydraulic energy, discharge, mechanical power and efficiency.

Efficiency calculation

Efficiency will be calculated from the mechanical power P exchanged with the electrical machine and the hydraulic power P_h exchanged with the water:

$\eta = P / P_h$ for a turbine,

$\eta = P_h / P$ □ for a pump.

Mechanical power determination

Mechanical power P is determined electrically by measuring the generator output (active output power) or motor input (active input power) P_a and taking into account the mechanical and the electrical losses P in the electrical machine and all other losses P , P and P specified in clause 2.3.8.3 of reference [1]:

$P = P_a + P_b + P_c + P_d + P_e$ for a turbine,

$P = P_a - P_b - P_c - P_d - P_e$ for a pump.

Mechanical and electrical losses P_b shall be calculated by linear interpolation of equipment technical data, taking into account the current value of power factor $\cos\varphi$ (ratio of the active power P_a to apparent power S):

$$\cos\varphi = \frac{P_a}{S}.$$

Apparent power S (kVA) formula calculation from active power P_a (kW) and reactive power P (kvar) is as follows:

$$S = \sqrt{P_a^2 + P_r^2}\ .$$

Hydraulic power evaluation

The evaluation of hydraulic power requires knowledge of the specific hydraulic energy E of the machine and of the mass flow rate ($\rho \cdot Q$) through the high pressure section (subscript 1):

$$P_h = E \cdot (\rho \cdot Q)_1 \pm \Delta P_h\ .$$

where ρ □is the water density and ΔP_h the hydraulic power correction (see clause 9.2.3 of reference [1]). For example, a small discharge q (e.g., cooling water) taken off between the discharge measuring section and a machine in turbine mode and not used for the turbine operation will induce a negative correction to P_h:

$$P_h = E \cdot (\rho \cdot Q)_1 - E \cdot (\rho \cdot q)\,.$$

Specific hydraulic energy determination

To determinate the specific hydraulic energy of the machine, it is necessary to evaluate the specific energy of water in the high pressure section (subscript 1) and low pressure section (subscript 2):

$$E = \bar{g} \cdot H = \frac{p_{abs1} - p_{abs2}}{\bar{\rho}} + \frac{v_1^2 - v_2^2}{2} + \bar{g} \cdot (z_1 - z_2) .$$

Taking into account the difference of elevation Z between machine section level and instrument level, the formula becomes:

$$E = \bar{g} \cdot H = \frac{p_{abs1} - p_{abs2}}{\bar{\rho}} + \frac{v_1^2 - v_2^2}{2} + \bar{g} \cdot (z_1 + Z_1 - z_2 - Z_2) .$$

The mean velocity v is the actual volume discharge passing through the measuring section divided by the area of that section ($v = Q / A$).

Variation of g with elevation is generally negligible and can be calculated for the reference level of the machine (z). Acceleration due to gravity g is a function of altitude z and latitude ϕ:

$$g = 9{,}7803 \cdot (1 + 0{,}0053 \cdot \sin^2 \phi) - 3 \cdot 10^{-6} \cdot z .$$

Mean water density $\bar{\rho}$□shall be calculated as the mean of densities at the two sections:

$$\bar{\rho} = \frac{\rho_1 + \rho_2}{2} \quad .$$

Water density is a function of water temperature Θ and absolute pressure p_{bs} (values for water density are given in table EII of reference [1]). The values ρ_1 and ρ_2 shall be calculated from p_{bs1} and p_{abs2} respectively, assuming the same water temperature Θ for both values.

Absolute pressure formula is:

$p_{abs1} = p_1 + p_{amb1}$, $p_{abs2} = p_2 + p_{amb2}$, and

$$p_{amb1} - p_{amb2} = -\rho_a \cdot \bar{g} \cdot (z_1 - z_2) .$$

where p is the gauge pressure, p_{amb} is the ambient pressure (absolute pressure of the ambient air) and ρ_a is the air density at the reference level of the machine. Air density in kg/m^3 is calculated as function of air temperature Θ_a in kelvin and ambient pressure p_a in Pa using the following formula:

$$\rho_a = \frac{p_{amb}}{\Theta_a} \cdot 3{,}4837 \cdot 10^{-3} .$$

For medium and high head machines, the difference in ambient pressure between 1 and 2 is neglected because ($z_1 - z_2$) is small compared to H:

$p_{a\;\;1} = p_{a\;\;2} = p_{a}$,

and therefore:

$$E = \bar{g} \cdot H = \frac{p_1 - p_2}{\bar{\rho}} + \frac{v_1^2 - v_2^2}{2} + \bar{g} \cdot (z_1 + Z_1 - z_2 - Z_2) .$$

At the low pressure side (and also at the high pressure side but only to low head machines), the specific energy of water can be evaluated from water level measurement $z_{2''}$ (tailwater level directly above the measuring section 2′):

$$\frac{p_{abs2}}{\bar{\rho}} + \frac{v_2^2}{2} + \bar{g} \cdot z_2 = \bar{g} \cdot z_{2''} + \frac{p_{amb2''}}{\bar{\rho}} + \frac{v_{2'}^2}{2} \mp E_{L2-2'} .$$

The section 2′ where the water level is measured should be as close as possible to the draft tube opening. To evaluate the mean velocity, the walls of the draft tube are supposed to extend up to section 2′, delineating the fictitious area of the section.

The loss between 2 and 2′, $E_{L2-2'}$, is subtracted for a turbine and added for a pump.

So, if section 2′ is chosen as measuring section, the specific hydraulic energy formula becomes:

$$E = \bar{g} \cdot H = \frac{p_1}{\bar{\rho}} + \frac{v_1^2 - v_{2'}^2}{2} + \bar{g} \cdot (z_1 + Z_1 - z_{2''}) \pm E_{L2-2'}$$

Run conditions

Each operating point will be obtained from one run. The number of measurements taken during a run will be at least five and the intervals between them will be defined for each experimentation site (around 4 minutes).

A run is considered valid if the following conditions are fulfilled (that is, if all measurements lie within the following limits during a run):

- variations of active power do not exceed $\pm 1{,}5\%$ of the average value of active power;
- variations of reactive power do not exceed $\pm 1{,}5\%$ of the average value of reactive power;
- variations of specific hydraulic energy do not exceed $\pm 1\%$ of the average value of specific hydraulic energy.

For each run the arithmetic average value of the measurements is computed for each quantity (Q, E, P). The efficiency is calculated on the basis of these values.

Conversion of turbine operating points results to the same specific hydraulic energy

Conversion of turbine operating points results to the same value of specific hydraulic energy $E_{sp} = \bar{g} \cdot H_{sp}$ (operating points average value) is made using affinity laws, assuming that the conditions of these laws are fulfilled:

$$\frac{Q_{sp}}{Q} = \left(\frac{E_{sp}}{E}\right)^{1/2}, \quad \frac{P_{sp}}{P} = \left(\frac{E_{sp}}{E}\right)^{3/2}, \quad \eta_{Esp} = \eta \ .$$

Weighted average efficiency calculation

Weighted average efficiency is calculated from the formula:

$$\eta_w = \frac{w_1 \cdot \eta_1 + w_2 \cdot \eta_2 + w_3 \cdot \eta_3 + \cdots}{w_1 + w_2 + w_3 + \cdots}$$

where $\eta_1, \eta_2, \eta_3, \ldots$ are the values of efficiency at the specified operating points and $w_1, w_2, w_3, \ldots$ are their weighting factors respectively.

Expected efficiency calculation

Turbine expected efficiency curve for the same value of specific hydraulic energy $E_{sp} = \bar{g} \cdot H_{sp}$ can be computed by interpolation of equipment technical data using turbine unit characteristics $n_{11} - Q_{11}$ and $n_{11} - P_{11}$ ($\alpha = const$, constant guide vane opening). Unit speed n_{11}, unit discharge Q_{11} and unit power P_{11} have the form:

$$n_{11} = \frac{n \cdot D}{\sqrt{E}}, \quad Q_{11} = \frac{Q}{D^2 \cdot \sqrt{E}} \quad \text{and} \quad P_{11} = \frac{P}{D^2 \sqrt{E^3}}$$

where n is the synchronous speed and D the turbine reference diameter.

Interpolation formulae, from two data sets $n'_{11}, Q'_{11}, P'_{11}$ and $n''_{11}, Q''_{11}, P''_{11}$ with $n'_{11} < n_{sp11} < n''_{11}$, that is, $E'' < E_{sp} < E'$, are:

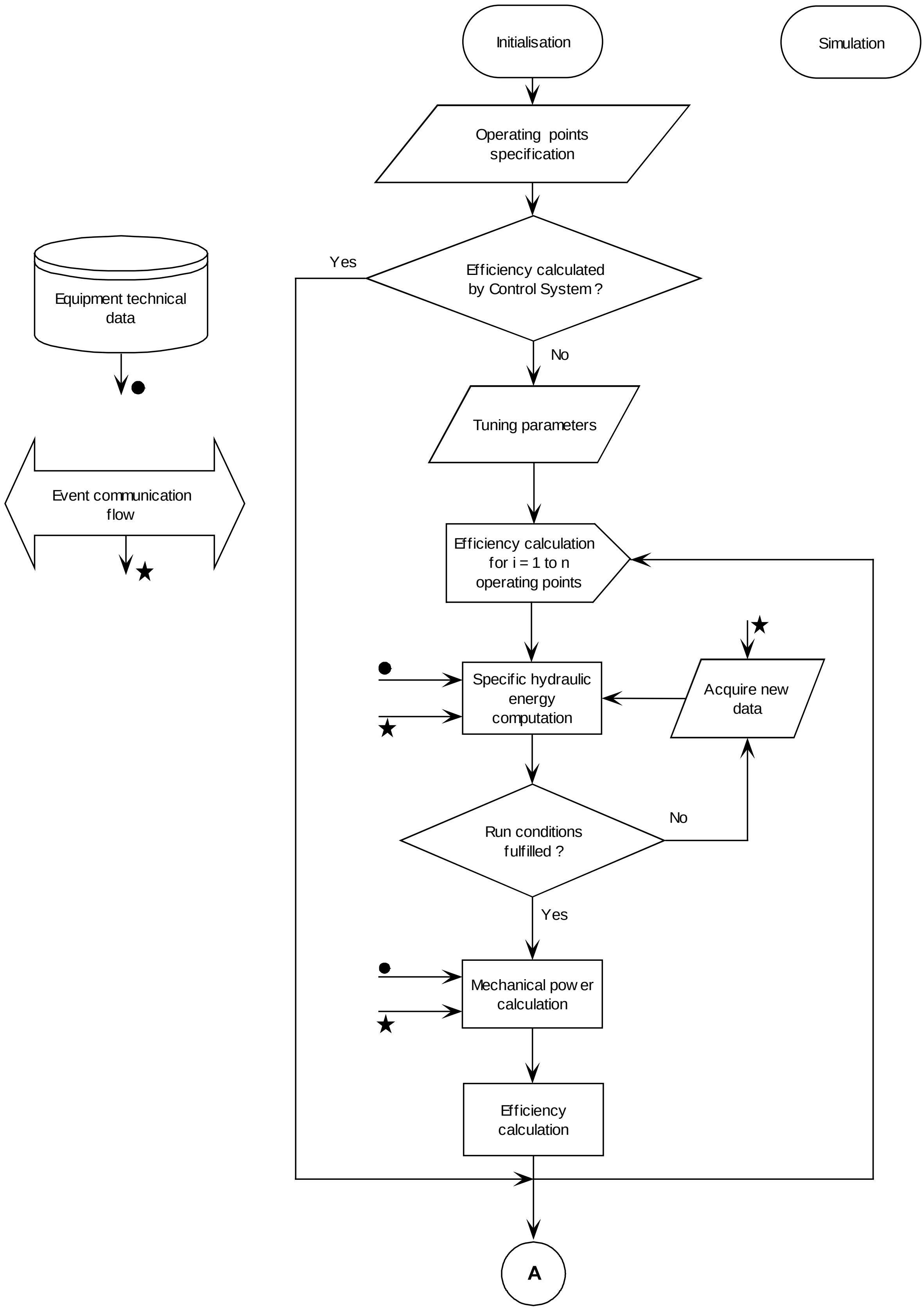
$$Q_{sp11} = Q'_{11} + (n_{11} - n'_{11}) \cdot \frac{Q''_{11} - Q'_{11}}{n''_{11} - n'_{11}} \quad \text{and} \quad P_{sp11} = P'_{11} + (n_{11} - n'_{11}) \cdot \frac{P''_{11} - P'_{11}}{n''_{11} - n'_{11}} \ .$$

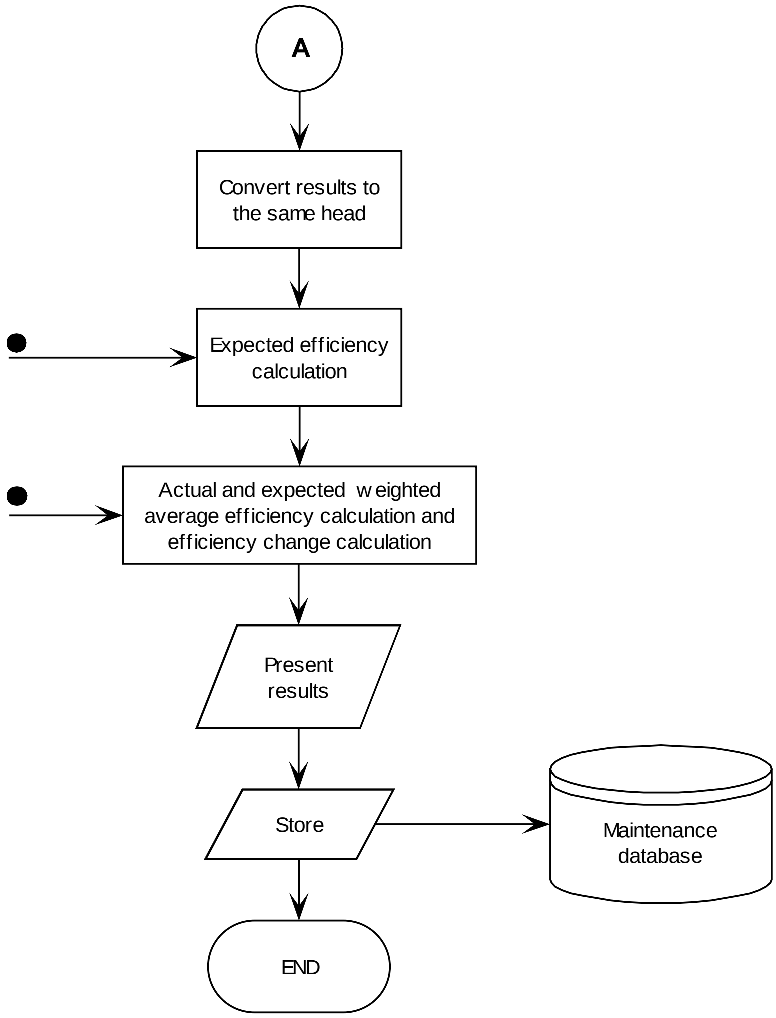
Therefore, the expected values of Q_{sp}, P_{sp} and η_{sp} are calculated as follows:

$$Q_{sp} = Q_{sp11} \cdot D^2 \cdot \sqrt{E_{sp}}, \quad P_{sp} = P_{sp11} \cdot D^2 \cdot \sqrt{E_{sp}^3} \quad \text{and} \quad \eta_{sp} = \frac{P_{sp}}{E_{sp} \cdot \bar{\rho} \cdot Q_{sp}} \ .$$

Overall algorithm

The overall algorithm is shown on the following figure:


Initialisation
Simulation
Operating points specification
Efficiency calculated by Control System ?
Yes
No
Equipment technical data
Tuning parameters
Event communication flow
Efficiency calculation for i = 1 to n operating points
Specific hydraulic energy computation
Acquire new data
Run conditions fulfilled ?
No
Yes
Mechanical pow er calculation
Efficiency calculation
A



7. INTERFACES

Maintenance operator interface must allow the dialogue with the control operator in order to request a new steady sate condition (that is, a new operating point), when the efficiency calculation is performed by the function.

Maintenance operator interface shall be capable of display both real-time data (measurements data) and historical data (equipment technical data).

System interface to the external world must allow to display the results (tables and graphics) remotely.

8. ERROR MANAGEMENT

Errors manager must display messages describing the cause of an error or a fault: network error, internal error, missing data, run conditions not fulfilled (if a predefined number of runs per operating point is exceeded), ...

9. CONSTRAINTS

The constraints to execute correctly the function are described in sections 5 and 6, namely the conditions under which the measurements must be performed .

10. HARDWARE AND SOFTWARE REQUIREMENTS

The function can be implemented using a standard PC hardware.

The output display should be of the SVGA type and able of presenting colour information.

11. TEST PLAN

It must be possible to test the function independently of data acquisition hardware and in a modular way. The components to test are described in section 6.

Errors cause simulation must also be possible.

The tuning parameters (number of measurements taken during a run and time interval between measurements) will be adjusted during experimentation phase.

12. REFERENCES

[1] IEC 41(1991): Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines

[2] IEC 994(1991): Guide for field measurements of vibrations and pulsations in hydraulic machines (turbines, storage pumps and pump-turbines)

[3] James W. Dally: Instrumentation for Engineering Measurements