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# Water saving options in hydropower by means of variable speed operation: A prototype study in a mid-head Francis turbine

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ABSTRACT

Nowadays, in order to mitigate the global warming effects, there is a need of renewable energy generation for the objective of carbon neutrality. In this context, hydropower plays a key role not only because the amount of renewable energy generated but also because it is a fundamental player to ensure the stability of the electrical grid, as one of the main dispatchable sources. Nevertheless, hydropower is facing nowadays with the climatological problem of the extreme droughts, that are expected to be more common in the upcoming years. Therefore, it has become more important than ever to use the water flowing through the rivers properly.

In this paper, the potentiality of using variable speed operation with the aim of increasing the overall efficiency of Francis turbines, which are the most widely used hydro turbines worldwide, is numerically explored. This implies to use less water to produce the same amount of electrical power. The study is based on an accurate modelling with real prototype data which has been made available for this study. It is shown that variable speed could improve the overall efficiency of the unit with respect to the constant speed generator, typically used in hydropower. While this idea has been mentioned in some previous studies, in this paper we also consider the electrical efficiency decrease of the variable speed technologies and restrictions of the unit regarding the electrical power generated. Results show that when the unit operates at some specific operating conditions, namely low heads at part load operations and high heads at maximum power, variable speed technologies could be used to save more than 2% of water with respect to the fixed speed unit. Main results and models of this paper can be used as a reference for future studies with similar type of units.

## 1. Introduction

Global warming and climate change is a serious threat for modern society and according to many studies it is being responsible for many natural disasters [1]. One of the main causes of the climate change and global warming are supposed to be the fossil fuels that are being used for electricity generation and transportation. Therefore, many international associations and governments claim that it is necessary to achieve the goal of carbon neutrality by 2050[2].

Hydropower is one of the main renewable energy producers and also plays a fundamental role in the stability of the electrical grid. This is because nowadays, hydropower is maybe the most important dispatchable energy source. This predominant role will be even more important in a scenario with a very fast grow of solar and wind energy which are also renewable energies but with the main issue that they are unpredictable to some extent.

One of the effects of the climate change, which is present nowadays, are the extreme droughts which have many negative environmental and social aspects and also affect the operation of hydropower. According to a recent report in 2022[3], in Portugal the potential hydroelectricity stored in reservoirs is less than half of the average in the previous five years. Therefore, for hydropower it is becoming more important than ever to reduce the amount of water used to produce the same amount of

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**Nomenclature**

| | |
|---|---|
| $D$ | diameter of the turbine |
| $f$ | frequency |
| $g$ | gravity |
| $H_g$ | gross head |
| $H_n$ | net head |
| $N$ | rotating speed |
| $n$ | number of poles |
| $n_{11}$ | speed factor |
| $P$ | power |
| $Q$ | flow rate |
| $q_{11}$ | flow rate factor |
| $s$ | slip factor |
| *Greek letters* | |
| $\eta$ | efficiency |
| $\rho$ | density of water |
| *Acronyms and subscripts* | |
| *BEP* | best efficiency point |
| *DFIG* | doubly fed induction generator |
| *FSFC* | Full size frequency converter |
| *SG* | synchronous Generator |
| *c* | converter |
| *e* | electrical |
| *g* | grid |
| *h* | hydraulic |
| *lc* | losses in the converter |
| *lg* | losses in the generator |
| *m* | mechanical |
| *r* | rated conditions |
| *sl* | slip |
| *st* | stator of the generator |

energy, or in other words to maximize the energy produced for a given amount of water. This can be only achieved by increasing the overall efficiency of the unit. Nevertheless, hydropower has the trend to work more and more in off-design imposed by the massive entrance of new renewable energies, and it is well known that in such conditions, the hydraulic efficiency of the unit decreases.

One possible solution to increase the efficiency is to use variable speed generators instead of the mostly used synchronous generators. In the present, there are few hydro turbines equipped with variable speed, although the idea of using it to increase the overall efficiency of the turbines has been discussed in some studies [4–7]. The main concept is that the unit can generally operate with a higher hydraulic efficiency if the rotating speed of the unit is increased/decreased with respect to the rotating speed imposed by the synchronous generator. This will increase the overall efficiency of the unit if the gain in hydraulic efficiency is capable to compensate extra losses of the electrical components (mainly converters) needed for variable speed generator.

In the study of Beyer about the pump storage unit in Goldistahl [4] the idea of improving the efficiency at part load conditions is only briefly mentioned. The author states that an efficiency advantage of approximately 10% is achieved when compared to fixed speed units (synchronous generator). Nevertheless, this possible improvement is not justified with previous references or efficiency curves of prototype turbines. In 2008, Pérez et al.[5] calculates the amount of extra energy that could be extracted by using variable speed in an irrigation reservoir. They estimated that thanks to the variable speed, the energy extracted in this particular set-up (a reservoir where irrigation is given priority over hydropower) could be increased by a 20%. Heckelsmueller [6] specifically states that variable speed is best used when the water head is below the design head. He estimated that speed variations about ± 20% are necessary to reach the maximum efficiency within a range of ± 40% of the design head. With the model used in that study it is estimated that an improvement of 22% of turbine efficiency at 60% of the design head can be achieved, while only 3% can be increased if the unit operates at 140% of the design head. Abubakirov et al.[7] also presents a study of the efficiency improvement by using variable speed, although not mean values for the efficiency improvement or energy gain are given. Generally, the numbers presented in those studies may be too optimistic, as they do not consider the fact that the electrical efficiency of a variable speed unit is lower than the electrical efficiency of a fixed speed unit (synchronous generators SG). Also, in these studies it is generally supposed that the electrical power can be always adjusted to reach the optimum hydraulic efficiency. Nevertheless, a more realistic situation is to consider that the electrical power, which is imposed by the electrical grid conditions, should be maintained constant even when the rotating speed changes.

There are mainly two types of variable speed generators (Double Fed Induction Generators DFIG and Full Size Frequency Converters FSFC) with a relatively mature technology as they have been widely used in aerogenerators [8]. Both technologies have been used in specific cases in hydropower on the prototype scale [9–12]. According to Hildinger and Ködding [9] DFIG is generally preferred for turbines over 100 MW as the cost of a FSFC is much higher than a DFIG for large units. Nevertheless, Schlunegger in 2014[11], documents the installation of a FSFC in Grimsel 2 pumped storage plant, which operates at around 100 MW as a pump and as turbine. Valavi and Nysveen in 2018[12] focus their review in the use of variable-speed in pump storage power plants. They stated that only 17 variable speed systems were in operation at the year of the publication, being most of them in Japan. When comparing both technologies (FSFC and DFIG), it can be concluded that FSFC is more versatile in terms of speed variation and less efficient than DFIG. Theoretical speed variation range in FSFC is practically unlimited [13]. DFIG has the main advantage that is more efficient, as only part of the power (slip power) passes through the converters. Nevertheless, the speed variation range in hydropower applications is generally assumed to be restricted to about ±10% of the nominal speed [13–17]. Further pros and cons of both technologies are widely discussed in the extensive reviews studies of variable speed operation in hydropower performed by Valavi and Nysveen [12] and by Iliev et al.[13].

Besides the efficiency improvement, there are another interesting and maybe more discussed applications of variable speed in Hydropower. Generally, variable speed is a very interesting application in pump-turbines where the main focus is to provide ancillary and regulation services for the power grid [14,18,19]. Nicolet et al. [14] present a simulation study showing the advantages of using a FSFC for providing ancillary services in a 210 MW pumped storage power plant. The authors show advantages such as fast transition from pump to turbine and the possibility of using the entire range of the unit in pump mode and in turbine mode. For units providing ancillary services, it is of paramount importance to regulate the output power as fast as possible. Because the time response of the electrical unit is much faster than the hydraulic unit, the output power can be changed quickly (scale of seconds) when FSFC or DFIG technologies are used. For example, Frades II (Portugal) is maybe the first large pump-turbine unit in Europe (around 400 MW) using DFIG technology. According to a recent report [18], variable speed clearly contributes to the stability of the Portuguese grid, as it can provide a much faster injection of power than conventional units in grid disturbances and a larger operating range. Furthermore, when used as a pump, the power absorbed can be also adjusted, increasing also the range as energy storage system [18]. This is a very interesting aspect to consider in a country with a high penetration of non-dispatchable energy sources such as wind and solar. These aspects, more related to the ancillary services that these units can provide to increase the flexibility of the power grid, are also discussed and analyzed in the aforementioned references [12–14].

From the theoretical benefits of using variable speed technologies, the present study is focused on the hydraulic efficiency improvement and the potentiality of saving water in a mid-head Francis turbine unit, which is the most widely used hydro turbine type. The study is made for both technologies, namely FSFC and DFIG. Compared to the previous references [4–7] considering the same topic, two main points will be included trying to make the study closer to the real operation of prototypes. On one side, the decrease of the electrical efficiency with respect to a fixed speed unit will be evaluated. On the other side it will be assumed that for a given operating condition, the unit using variable speed has to keep the same electrical power according to the dispatching demand, which do not necessarily imply to operate at the maximum efficiency possible.

The study has been made in a mid-head Francis unit, which is one of the demonstrators of the XFLEX Hydro project [20]. The unit has been accurately modelled, considering the losses in the hydraulic circuit and also the hydraulic, mechanical and generator efficiency and actual operating ranges. It is shown that a significant amount of water can be saved if the unit operates out of the design head. Main results and models used in this study may be extrapolated to Francis units with similar specific speeds and operating heads.

## 2. Variable speed for improving the hydraulic efficiency maintaining the electrical power generated

In a hydraulic turbine unit, the electrical power depends mainly on the available net head, the flow rate and the different losses occurring in the transformation from hydraulic power to electrical power. These include the hydraulic losses, mechanical losses and generator losses. Hydraulic losses are by far the most important ones, especially when the unit works in off-design conditions. The conversion from available hydraulic power to electrical power can be expressed as (Eq.1) [21]:

$$P_e = P_h \bullet \eta = \rho g Q H_n \eta = \rho g Q H_n \eta_e \eta_m \eta_h; \quad H_n \approx H_g - kQ^2 \tag{1}$$

$H_n(m)$ is the net head, $Q(\frac{m^3}{s})$ is the flow rate passing through the turbine, $\rho(\frac{kg}{m^3})$ is the density,$g(\frac{m}{s^2})$ gravity and $\eta$ is the global efficiency of the turbine, which may be separated as follows.$\eta_e$ is the electrical efficiency which accounts for the losses in the generator, $\eta_m$ is the mechanical efficiency which considers the friction losses on the shaft and $\eta_h$is the hydraulic efficiency which considers the hydraulic losses in the turbine runner. The net head $H_n(m)$ can be calculated considering the gross head $H_g$ (difference of the head race level and tail race level) and the losses in the hydraulic circuit, which are proportional to $Q^2$ [21].

According to the dimensional analysis theory applied to hydraulic machinery, the hydraulic efficiency depends on the two following parameters (Eq.2)[21,22]:

$$n_{11} = \frac{ND}{\sqrt{H_n}} \qquad q_{11} = \frac{Q}{D^2\sqrt{H_n}} \tag{2}$$

$N$ is the rotating speed of the unit (usually in *rpm*), $D$ the reference diameter of the runner (usually expressed in *m*), $H_n$ the net head (*m*) and $Q$ the flow rate (usually in *l/s*). Representations of the constant hydraulic efficiency curves as a function of the $n_{11}, q_{11}$ are known as Hill-Charts.

To represent the idea of variable speed operation, the Hill-Chart on Fig. 1 is used. In this Hill-Chart the constant hydraulic efficiency curves, constant electric power and constant distributor position are represented. As a reference point, it is considered the operation of a specific unit at 17 MW, with a distributor position of 20° and hydraulic efficiency $\eta_h = 0.93$ (Fig. 1). Assuming that the unit works under a relatively constant $H_g$ (which cannot be varied rapidly), the parameter $n_{11}$ will remain nearby constant for a synchronous generator as $N, D$ are fixed (a small reduction of $H_n$ is expected when increasing $Q$ due to hydraulic losses in the pipes as seen in Eq.1). Then, the operating point can be only varied by increasing/decreasing the angle of the distributor (represented with green arrows on Fig. 1). This will move the unit to a new operating point $n_{11}, q_{11}$, with a new flow rate $Q$, new efficiency $\eta_h$ and new generated power $P_e$.

The idea of using variable speed, permits to move to another operating point with the same electrical power $P_e$ (maintaining the gross head $H_g$), different flow rate $Q$ and different efficiency $\eta_h$. Variable speed operation is represented in Fig. 1 with black arrows. Following the black lines in Fig. 1 results in an operating point with the same electrical power $P_e$, higher hydraulic efficiency $\eta_h$ and less flow rate. This is an interesting benefit, as the unit can produce the same output $P_e$ with less water.

## 3. Model of a mid-head Francis unit prototype in operation

In order to obtain the constant electrical power curves (Fig. 1) of a real prototype, the losses in the hydraulic circuit (inlet and outlet pipes), the hydraulic efficiency of the runner, the mechanical efficiency and the electrical efficiency have to be considered. For this study, a model

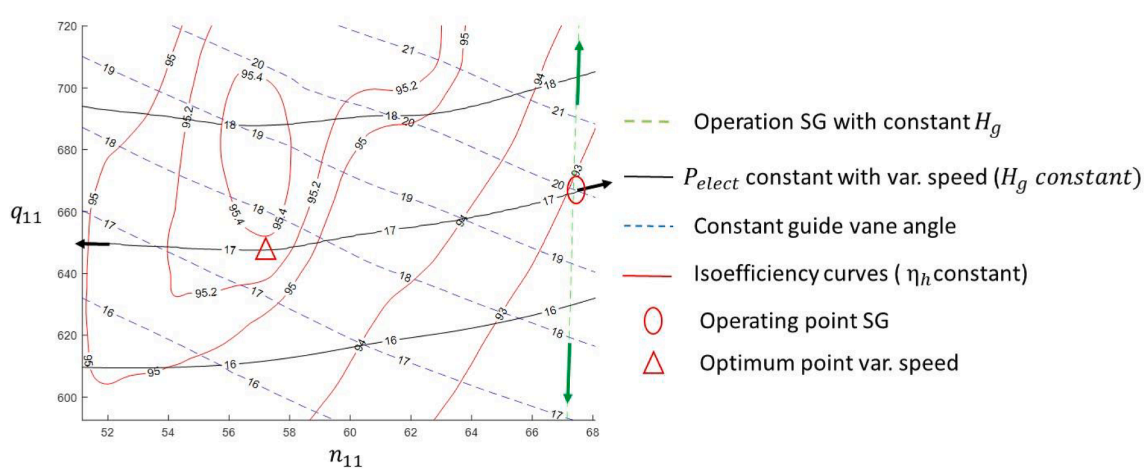


**Fig. 1.** Operation of the turbine in the $q_{11}, n_{11}$ coordinates. Operation of the synchronous generator with constant gross head $H_g$. Operation with variable speed and constant $H_g$ and generated power..$P_e$

considering all these losses has been created. The inputs for the model are the available $H_g$ and the electrical power $P_e$. Three different types of generators have been considered: fixed speed unit with a synchronous generator SG, DFIG with a limited variable speed range and a FSFC with a full variable speed range.

For the fixed speed unit, with the given inputs $H_g$ and $P_e$, there is a single operating point and thus a single $Q$ possible. For the variable speed units, there are many possible $Q$ depending on the rotating speed N. Therefore, when modelling and simulating the variable speed units, N is also used as an input parameter, which is optimized to minimize the flow rate. Finally, to analyze the water saving options with respect to the synchronous machine, the flow rates obtained for the variable speed options are compared against the synchronous generator unit. In the following sections, the different considerations and assumptions used for the modelling of a mid-head Francis unit are explained in detail.

### 3.1. Main characteristics of the prototype used for the modelling

The simulation model used in this study is based on the prototype data of a mid-head Francis turbine located in Portugal (Caniçada) and it is operated by Energias de Portugal (EDP). In frame of the project XFLEX Hydro, the needed data for this study was made available. The rated characteristics of the unit are listed on Table 1.

### 3.2. Relationship between $H_g$, Q and $H_n$

The available net head $H_n$ for the turbine depends on the gross-head $H_g$ and the losses in the hydraulic circuit (inlet and outlet pipes), which are almost proportional to $Q^2$for turbulent flows [21]. During the commissioning tests of the unit, these losses were accurately measured. As in many mid and high head units, the gross head $H_g$ is mainly determined by the upstream level. This level typically follows a seasonal trend in the year, with a maximum in spring-summer and a minimum in autumn–winter. In the considered turbine, with a relatively long outlet conduit, the approximated net head obtained by regression ($R^2$= 0.989) is measured to be (Eq.3):

$$H_n \approx H_g - 0.0046Q^2 \tag{3}$$

Note that this measured characteristic follows the form of Eq.1. $H_g$, $H_n$ are expressed in $m$ and $Q$ in $m^3/s$.

### 3.3. Hydraulic losses and hydraulic efficiency

The hydraulic losses are the most important ones and specially when the unit operates in off-design conditions. Hydraulic losses consider the dissipated energy of the water passing through the turbine runner, and therefore better designed turbines will have a better efficiency. At the design point, also known as Best Efficiency Point (BEP), the hydraulic losses are minimal, and therefore the hydraulic efficiency $\eta_h$ is maximal. The whole hydraulic efficiency of the present unit is represented in the following Hill Chart (Fig. 2). Although this Hill-Chart is a particular case of a relatively new and well-designed mid-head Francis runner (2017) it may be representative of turbines in the same specific range and manufacturing period according to the basic design ideas of optimal design in turbo machinery [23].

To model the actual prototype, the information contained in Fig. 2 was digitized with the web application *WebPlotDigitzer* [24].

**Table 1**
Rated characteristics of the prototype turbine used for the model.

| Rated Power $P_r$ | 32 MW |
|---|---|
| Rated Gross Head | 121 $m$ |
| Rated Flow rate | 34 m^3/s |
| Rotating speed (synchronous gen.) | 300 rpm |
| Outer diameter | 2.014 $m$ |

Particularly, the constant efficiency curves (in green) and the constant guide vane opening curves were obtained in the $n_{11}, q_{11}$ coordinates.

Then a grid consisting of 271 points in the $n_{11}$ coordinate (from $n_{11}$ = 45to $n_{11}$ = 72 with $\Delta n_{11}$= 0.1) and 701 points in the $q_{11}$ coordinate (from $q_{11}$ = 250to $q_{11}$ = 950 with $\Delta q_{11}$ = 1) was generated. The efficiency was then obtained for all the 271x701 grid points. This process was done with the surface fitting code *gridfit* from MATLAB [25].

### 3.4. Friction losses and mechanical efficiency

The mechanical efficiency was also measured during the commissioning tests. Mechanical efficiency considers the mechanical losses such as friction of the bearings, friction of the rotating structure with the surrounding air, disk losses and other type of minor losses. In the present unit the mechanical efficiency is given by the following expression (Eq.4):

$$\eta_m = 0.004952\frac{P_e}{P_r} + 0.992182 for \frac{P_e}{P_r} \in [0.25, 1.1] \tag{4}$$

$\eta_m$ is the mechanical efficiency and $P_e$ is the electrical power generated. $P_r$ is the rated power. In the measured range, the mechanical efficiency was always higher than 99%.

### 3.5. Electrical losses and electrical efficiency

The actual unit operates with a synchronous generator, where the electrical efficiency was also measured during the commissioning tests. For the FSFC and DFIG this efficiency is modeled based on the existing literature.

#### 3.5.1. Synchronous generator (SG)

The electrical efficiency in a synchronous generator considers the stray losses, friction and windage losses in the generator structure, core losses and $I^2R$ losses [26]. The efficiency curve of the SG was determined during the commissioning tests for $\frac{P_e}{P_r} \in [0.25, 1.1]$. The measured data can be approximated with an $R^2$ = 0.9998 with the following expression (Eq.5):

$$\eta_{SG} = -0.075961\left(\frac{P_e}{P_r}\right)^4 + 0.311295\left(\frac{P_e}{P_r}\right)^3 - 0.474741\left(\frac{P_e}{P_r}\right)^2 + 0.323532\left(\frac{P_e}{P_r}\right) + 0.894357; \eta_{SG,max} = 0.98 \tag{5}$$

For further steps, it is assumed that the maximum efficiency of this generator is 0.98. It is also important to mention that this curve was obtained for a power factor of 1. According to the historical data, this unit always works with a power factor of 0.995, regardless of the active power $P_e$generated.

#### 3.5.2. Model for the Full Size frequency converter (FSFC)

For a FSFC, all the generated power in the synchronous generator passes through the converters (Fig. 3). Here we assume that the converters have an efficiency of 98.5% [9,14] so that the efficiency curves of the synchronous generator (Eq.5) are downshifted in the entire range by a factor of 0.985[13], which gives the efficiency in Eq.6. We also assume that in this configuration, the range of speed variation of the rotor is not restricted [13].

$$\eta_{FSFC} = \eta_{SG} \bullet 0.985 \tag{6}$$

#### 3.5.3 Model for the Double Fed Induction generator (DFIG)

The DFIG model is represented in Fig. 4. In this configuration, only part of the power, namely slip-power, $P_{slip}$ passes through the converters.

The first relevant parameter to be defined in the DFIG is the slip $s$ (Eq. (7)) [26]:

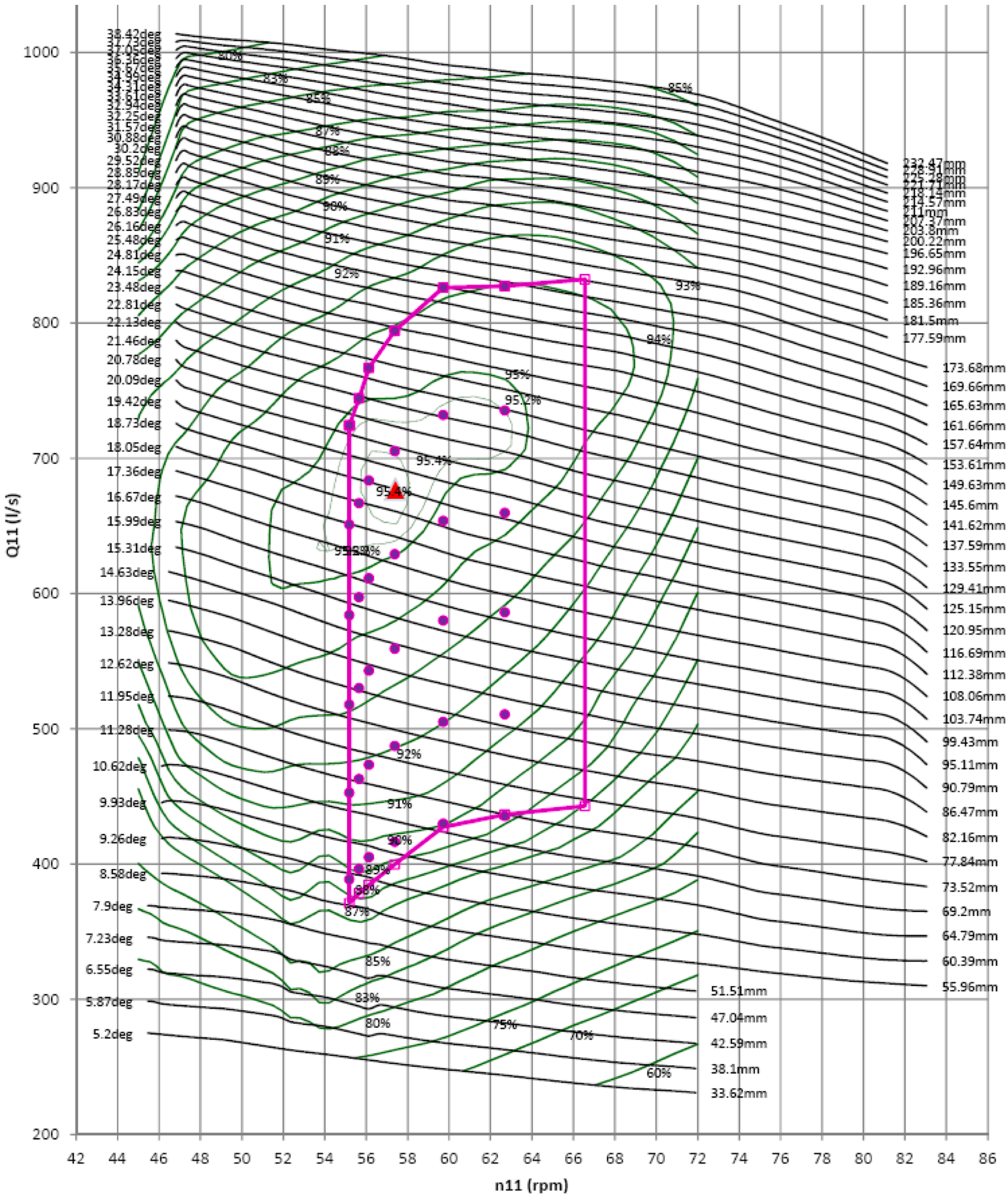


**Fig. 2.** Hill- Chart of the analyzed unit.

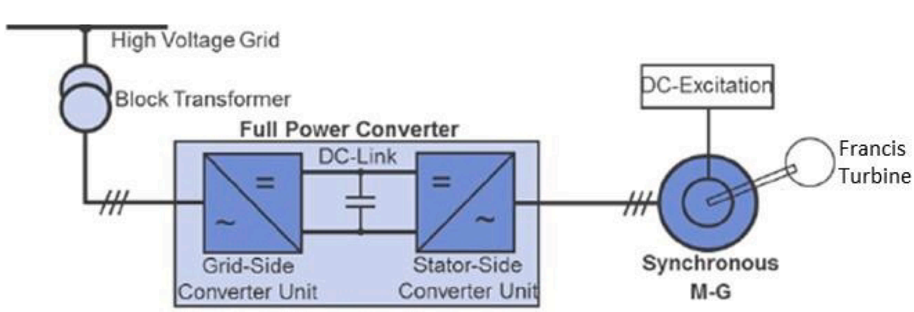


**Fig. 3.** FSFC for a Francis Turbine. Figure reproduced from [9] with permit from the authors.

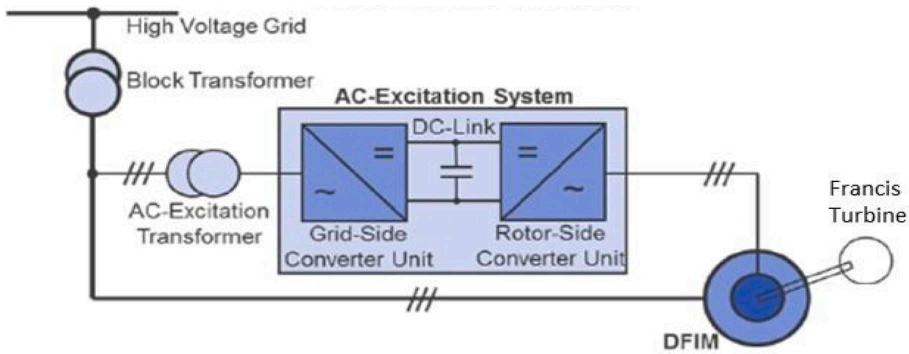


**Fig. 4.** DFIG for a Francis Turbine. Figure reproduced from [9] with permit from authors.

$$s = \frac{f_{SG} - f_m}{f_{SG}} with f_{SG} \bullet n = f_{gr} \tag{7}$$

$f_{SG}$is the synchronous frequency, and for a SG it is exactly the mechanical rotating speed of the rotor in *Hz*. This number multiplied by the pair of poles in the generator $n$ is the grid frequency $f_{gr}$. $f_m$ is the mechanical rotating speed of the rotor, which in case of variable speed units can be different from $f_{SG}$. In this case, we restrict $f_m$ to be in the range $[0.9f_{sg}, 1.1f_{sg}]$ according to the limitation of $\pm 10\%$ assumed in previous studies [9,13,14]. If the slip is positive, the unit operates in super-synchronous mode and if the slip is negative in sub-synchronous mode. If the slip is zero, then the unit rotates at the synchronous frequency $f_{SG}$, and it is approximated with the synchronous generator efficiency described in Eq. (5).

The slip power, $P_{sl}$ can be calculated as (Eq.8) [27]:

$$P_{sl} \approx s \bullet P_{st} \tag{8}$$

In order to model the losses in the DFIG, the following power flow diagram (Fig. 5) will be considered (adapted from the DFIG power flow model shown in [28]).

This power flow relates the mechanical power on the turbine shaft $P_m$, the slip power $P_{sl}$, the power on the stator side of the DFIG $P_{st}$ and the electrical power generated $P_e$. In this model,$P_{st}$ is calculated using the approximated efficiency of the synchronous generator $\eta_{SG}$ described in Section 2.4.1. This relationship is expressed with Eq.10 for both operating modes:

$$P_{st} = P_m + P_{sl} - P_{lg} = (P_m + P_{sl})\eta_{SG} = (P_m - sP_{st})\eta_{SG} \tag{10}$$

It is important to notice that in sub-synchronous mode, ($s < 0$) the combined power $P_m - sP_{st}$ is higher than in super-synchronous mode ($s > 0$) and therefore the losses in the generator $P_{lg}$, which are the most important ones, are also higher. Therefore, at sub-synchronous regimes, the electrical efficiency will be lowered [28].

The electrical power $P_e$ can be calculated as (Eq.11):

$$P_e = P_{st} - \frac{P_{sl}}{\eta_c} for s < 0 (sub - synchronous)$$
$$P_e = P_{st} + P_{sl}\eta_c for s > 0 (sub - synchronous) \tag{11}$$

Where the efficiency of the converters $\eta_c$ is assumed to be 0.985 as in the previous section. Finally, the overall efficiency of the DFIG is defined as follows (Eq.12):

$$\eta_{DFIG} = P_e / P_m \tag{12}$$

With the described approximated model, when $s = 0$, $\eta_{DFIG}$is considered to be the same as the actual synchronous generator $\eta_{SG}$. For sub-synchronous regime, $\eta_{DFIG}$ will be substantially lower due to the higher losses in the generator $P_{lg}$ and for the super-synchronous mode, the efficiency will be slightly higher. Exactly the same trend is observed in [28].

### 3.6. Restrictions considered for the study

For the present study, the following restrictions based on typical operation of hydraulic units are assumed. The main objective is to compare the water consumption of the actual synchronous generator against the variable speed generators technologies (FSFC and DFIG).

- The electrical power has to be maintained constant when the rotating speed of the generator is changed.
- When changing the rotating speed, the gross head is maintained constant as it is given by the upstream reservoir level and this level cannot vary rapidly.
- For the synchronous generator case, the electrical power generated by the unit can be only modified by opening/closing the guide vanes (Fig. 1). This will increase/reduce the passing flow rate $Q$ and therefore the electrical Power $P_e$ (Eq.1). This will also increase/decrease all the efficiencies described in this section. The electrical efficiency of the synchronous generator is assumed to be $\eta_{SG}$
- For the FSFC, the rotating speed of the turbine can be changed, and it is not necessarily the synchronous speed $f_{sg}$. This permits to move the

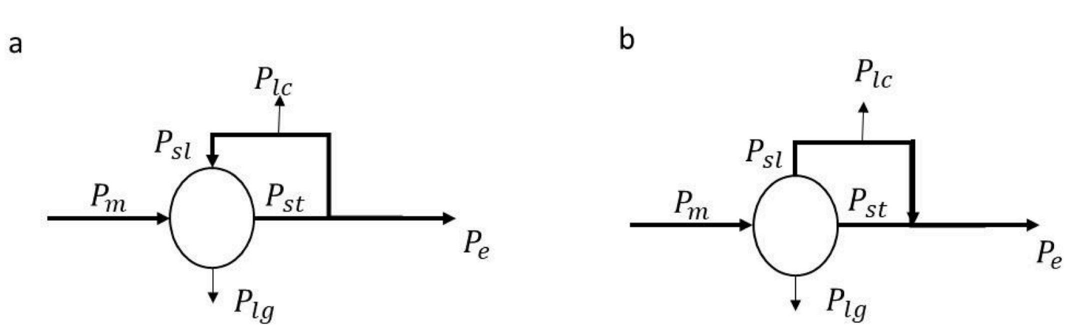


**Fig. 5.** Operation of the DFIG. Sub-synchronous (a) and super-synchronous mode (b).

unit to many operating points in the hill-chart without changing the electrical power (Fig. 1). The criterium is to operate always at the minimum $q_{11}$, which will minimize the flow rate $Q$ passing through the turbine. The efficiency of the generator is assumed to be $\eta_{FSFC}$

- For the DFIG the same criteria as for the FSFC are used. In this case, the rotating speed is restricted to $\pm$ *10%* of the synchronous speed. The efficiency of the generator is assumed to be $\eta_{DFIG}$.

## 4. Results

Results of this study will be normalized against the design parameters of the unit operating with the SG at the synchronous speed in the Best Efficiency Point (BEP). This point corresponds to the point with the maximum $\eta_h$, which is represented in Fig. 6 and the corresponding parameters are listed in Table 2.

### 4.1. Operation with variable speed. Constant electrical power curves

The operation with variable speed is summarized in this section. In Fig. 7a, the unit operates in the design gross head $H_{g_{SG}}$a nd optimal power $P_{e_{SG}}$, where $\eta_h$is maximum. Constant electric power curves for the *FSFC, DFIG* and evolution of the mechanical power $P_m$ are represented. In order to maintain the electrical power and increase/decrease the rotating speed, the guide vanes have to be opened/closed as seen in the figure. In this situation it is obviously not interesting to modify the rotating speed if the objective is to minimize $Q$ (which is equivalent to minimize $q_{11}$) as the unit already works at BEP. It is interesting to see that with the *FSFC*; the water consumption is a little bit higher, as the electrical efficiency is lower than for the *DFIG* at synchronous speed.

In Fig. 7b the unit operates in a higher gross head and electrical power than before. In this situation, the unit works out of the *BEP*. Nevertheless, by increasing the rotating speed (and opening the guide vanes) a close condition to the *BEP* can be reached, maintaining the electric power. For this particular design, the flow rate is slightly reduced as the hydraulic efficiency is already very high even the machine operates in off-design conditions. Again, the *DFIG* shows a better performance and the limitation of the rotating speed variation for this technology is not affecting the optimum.

The last situation (Fig. 7c) represents the unit operating in a lower gross head and electrical power. Again, when the turbine operates with a SG, the unit is far from the *BEP*. In this case, by reducing the rotating speed and closing the guide vanes, the *BEP* can be reached with variable

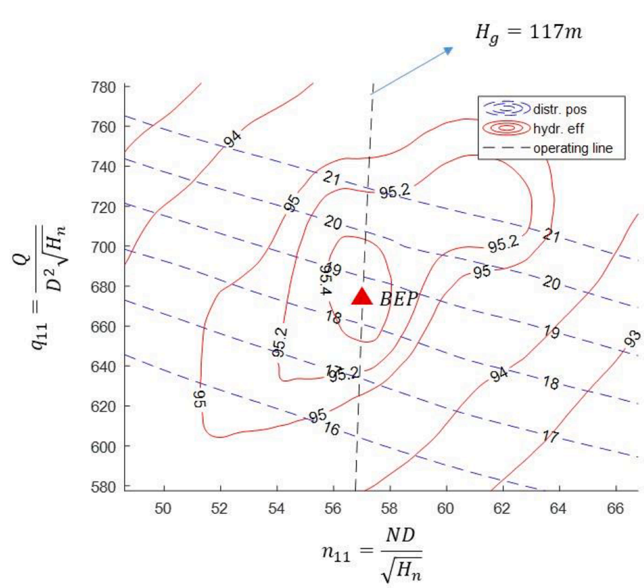


**Fig. 6.** Best Efficiency Point of the Unit (BEP).

**Table 2**
Operating Parameters at the BEP for the turbine unit with the SG.

| Gross Head ($H_{g_{SG}}$) | $117m$ | $q_{11,BEP}$ | $681 l/s \bullet m^{-5/2}$ |
|---|---|---|---|
| Net Head$_{BEP}$ ($H_{n_{SG}}$) | $112.3m$ | Distributor angle | $18.8^{\circ}$ |
| Flow rate ($Q_{SG}$) | $29.3 m^3/s$ | $\eta_h$ | 95.47% |
| $P_{e_{SG}}$ | $30MW$ | $\eta_{m_{SG}}$ | 99.67% |
| $n_{11,BEP}$ | $57 min^{-1} \bullet m^{1/2}$ | $\eta_{e_{SG}}$ | 97.82% |

speed and the flow rate passing through the turbine is reduced. In this situation, the $\pm$ *10%* restriction for the DFIG is still not important for reaching the optimum although it can be appreciated that by further reducing the head (moving to a higher $n_{11}$) this limitation would affect.

### 4.2. Increase of hydraulic efficiency and reduction of flow rate with DFIG and FSFC

Taking into account the main behavior observed in Fig. 7, in this section the improvement of $\eta_h$ when using FSFC and DFIG technologies has been calculated for every operating point $n_{11}, q_{11}$. When the unit operates with the SG and considering that its operation is restricted by a constant gross head $H_g$, only some specific $n_{11}, q_{11}$ operating points can be reached. All these points lay in a curve (which is not a vertical line due to losses in hydraulic circuit) corresponding to the given gross head $H_g$. These curves are represented for several $H_g$ in Fig. 8a. Low head curves correspond to high $n_{11}$ and vice versa. Operating points with high $q_{11}$ corresponds to high loads (high $P_e$,$Q$ and distributor more opened).

Variable speed technologies permit to move in an almost horizontal line as seen in Fig. 7. Therefore, the areas of the Hill-Chart with close and inclined constant efficiency curves are potential areas of improvement. These areas correspond mainly to low $H_g$ and low load (low $P_e$, $Q$) operation of the machine (right-bottom of the Hill-Chart) and high head and high load operation (top-left of the Hill-Chart). This fact is confirmed in the results shown in Fig. 8b and Fig. 8d. With variable speed, it is possible to improve the hydraulic efficiency up to a 2–3% in these areas. Both technologies show similar capability for improvement, as seen in the respective figures. For very extreme off-design heads, the FSFC technology shows a better performance as it does not have the limitation of ±10% assumed for the DFIG.

Finally, the most important result corresponds to the possible flow-rate reduction with variable speed. To analyze this result, we need to consider the potential improvement of $\eta_h$ but also the reduction of $\eta_e$ with respect to the SG (discussed in Section 3.4). In this case, the deterioration of $\eta_e$ is worse for the *FSFC*. Therefore, as seen in Fig. 8c and Fig. 8e, the potentiality to reduce the flow rate in the unit is higher for the *DFIG* unit, especially in the operating areas mentioned before (low head and low load; high head and high load). This reduction can be about *2–3%* in the most extreme conditions (right-bottom of the Hill-Chart).

### 4.3. Amount of water saved in different scenarios

Finally, some results regarding the potential reduction of water consumed by the unit assuming different annual scenarios (in a simplified way) are presented. It is assumed that $H_g$ follows the typical pattern of a maximum during spring and a minimum after 6 months (autumn). If the unit is properly designed for the hydroelectric installation (considering the averaged levels in the upstream and downstream reservoirs), then the design head and therefore the BEP is assumed to be in the center of the operating area. Together with the load variation of the unit, this will describe an operating area every half year, as represented in Fig. 9. In order to make the results more general and representative for more units, it is assumed a uniform operation inside this area.

Regarding the head variation, with respect to the design head $H_{g_{SG}}$, two different situations are assumed; ±10% of variation and a more

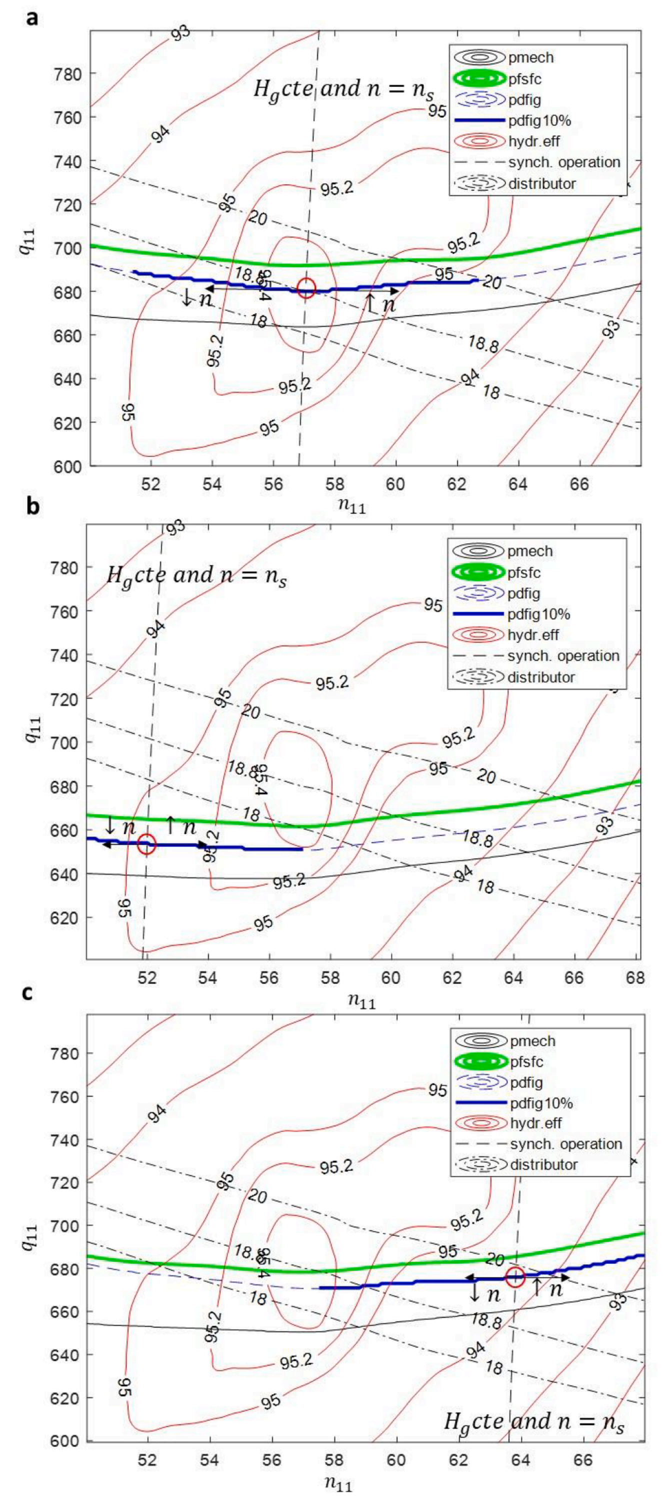


**Fig. 7.** Operation with variable speed. DFIG and FSFC. a) Operating at $H_g/H_{g-SG} = 1$ and $P_e/P_{e-SG} = 1$ b) Operating at $H_g/H_{g-SG} = 1.2$ and $P_e/P_{e-SG} = 1.26$ c) Operating at $H_g/H_{g-SG} = 0.8$ and..$P_e/P_{e-SG} = 0.72$

extreme variation of ±20% with respect to $H_{g_{SG}}$. These approximate ranges have been defined based on our previous experiences with similar types of units (see for example the considered prototypes in [29,30]).

Two different scenarios are also considered for the load variation. In the present operation of the unit, the flow rate range is defined with the following limits $[0.54Q_{SG}\text{-}1.16Q_{SG}]$. These limits are defined considering the design of the unit and, in a more general context, considering the management of the water resources and the hydric restrictions given by national laws. Similar $Q$ ranges, are also found in similar type of units [29,30]. The first scenario considers that the unit is using for regulating purposes, and therefore it operates around the entire range. The second scenario is that the unit is operated in a more conservative way around the BEP and then the range $[0.8Q_{SG}\text{-}1.16Q_{SG}]$.

Assuming the four different operating areas represented in Fig. 9, the amount of water saved with respect to the synchronous unit has been calculated. For this calculation, it is considered that the synchronous unit and the variable speed unit produce exactly the same electrical power at every time.

Fig. 10 shows the relative difference (%) of water consumed by the DFIG machine and the FSFC machine with respect to the synchronous machine. These values represent an approximated averaged value of the areas defined in Fig. 9 transposed to Fig. 8c & Fig. 8e. Positive percentages mean that the variable speed unit would consume less water in that scenario than the synchronous machine. The better performance of the DFIG is clear, and it is due to the higher electrical efficiency. In fact, in one-year average, the FSFC unit will consume more water than the synchronous unit. Nevertheless, if FSFC is already installed for other purposes (such as flexibility of the unit [14]) it can be used to save water in extreme off design conditions (Fig. 8).

It is also important to remark that the results for the FSFC have been obtained considering that the converters are always connected to the synchronous generator, and therefore they always deteriorate the electric efficiency. Nevertheless, as discussed in [9] a solution to improve this issue is to have a switch system to connect/disconnect the full power converter when necessary. This would improve the results for the FSFC technology.

The amount of water saved would be even larger if the operating ranges of the unit are increased. For example, it has been checked that if the unit would operate with $0.4\Delta H_{g_{SG}}$ and 0.86 $\Delta Q_{SG}$ (instead of $0.4\Delta H_{g_{SG}}$; 0.62 $\Delta Q_{SG}$) the amount of water saved in a long-term operation would be doubled (0.55% vs 0.28% for the scenario a represented in Fig. 9). Finally, it is worth to mention that in the near future it is expected that, hydropower units will have to operate with lower heads and flow rates than they were designed for, due to extreme droughts. This particular situation will increase the water saved with variable speed technologies, as it is precisely the area of the Hill-Chart where the range of hydraulic efficiency improvement is maximum (see Fig. 8b and Fig. 8d).

To finish this section, we calculate how many $hm^3$ could save the DFIG unit with respect to the actual prototype in the different scenarios assumed. These results are shown in Fig. 11. When operating the unit in scenario c and d (Fig. 8) more water is needed as the unit works with higher flow rates (Fig. 11a). In terms of water saving, as seen in Fig. 11b, it is estimated that between 1 and 1.5 $hm^3$ ($1 - 1.5 \times 10^9$ liters) could be saved with the DFIG in one year of operation for similar type of units. This roughly represents 1% of the useful capacity of the actual dam's reservoir. This percentage would be further increased for larger capacity units as the nominal flow rate is higher.

## 5. Conclusions

In this study, the potentiality of using variable speed technology to save water has been investigated with accurate data of a mid-head prototype, which is one of the demonstrators of the EU project XFLEX-Hydro. Thanks to the information during the commissioning tests and the Hill-Chart of the unit, a realistic model could be made. Results and conclusions of these study may be useful for mid-head Francis units.

The two different technologies used for variable speed hydro units have been analyzed and compared. These are the Doubly Fed Induction Generator (DFIG) and the Full Size Frequency Converter (FSFC). It is shown that both technologies can help to reduce the passing flow rate

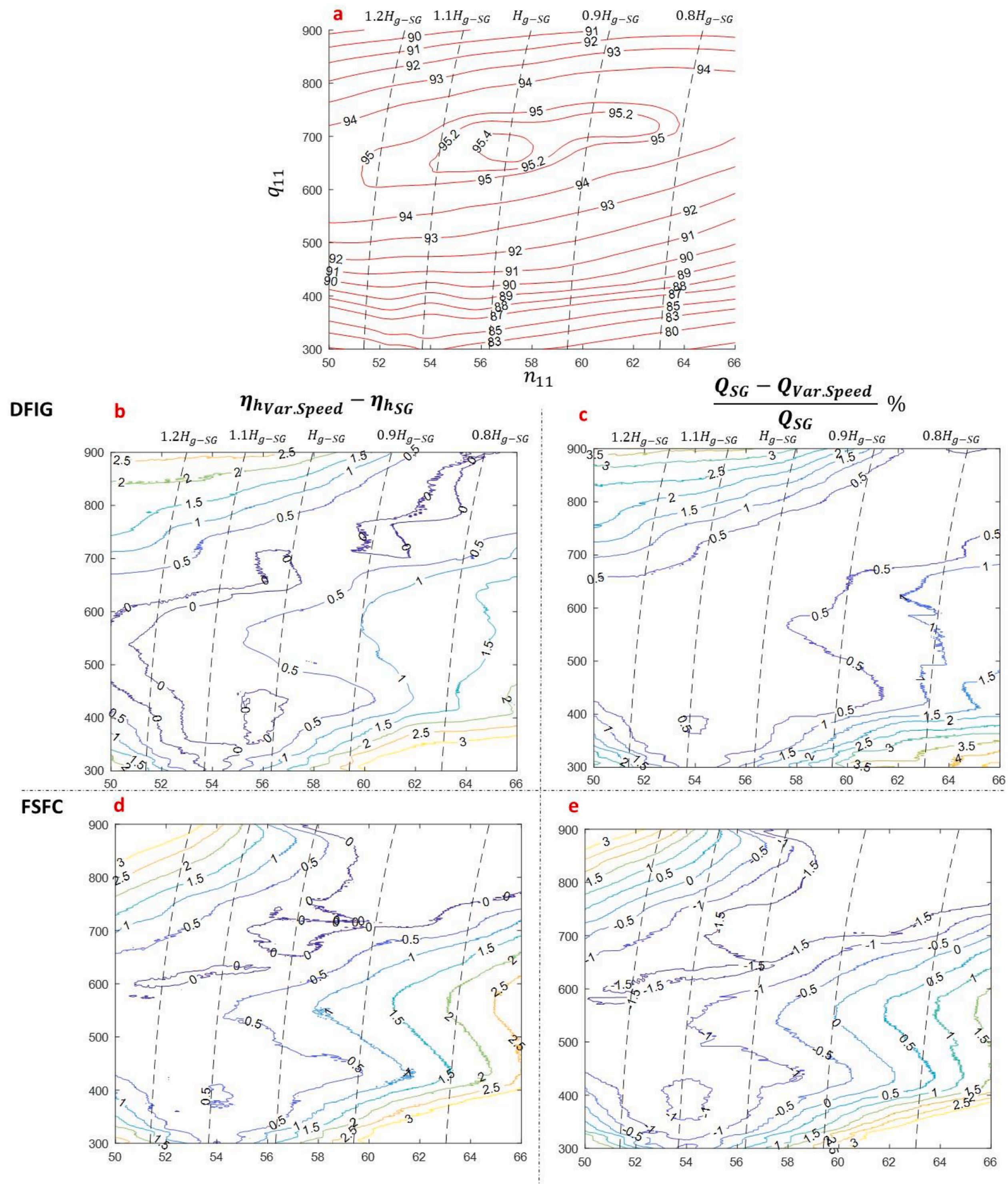


**Fig. 8.** A) hill-chart of the mid-head francis unit. lines of operation with constant $H_g$ and synchronous machine. b& d) Improvement of hydraulic efficiency (%) for every $n_{11}, q_{11}$. DFIG and FSFC technologies c& e) Reduction of flow rate Q with respect to the synchronous machine (%). DFIG and FSFC technologies.

with respect to the typical synchronous generator unit, especially when the unit operates in extreme off-design conditions (higher/lower heads than the design head). It is estimated that the hydraulic efficiency can be improved around 3% when the unit operates at very high/low heads, with respect to the design head.

In the present study, the decrease of the electrical efficiency for variable speed technologies has been considered. In our model, which is also in accordance to previous studies, the DFIG has a higher electrical efficiency than the FSFC. This advantage in electrical efficiency of the DFIG with respect to the FSFC can be 1% to 1.5% close to the BEP, and reduces when the unit operates in off-design conditions. Therefore, when considering the whole unit, the DFIG shows better water saving options.

Four different annual-term scenarios have been simulated with different head and load variations. It is shown, that water saving options are higher for units working with a high variation range of head and

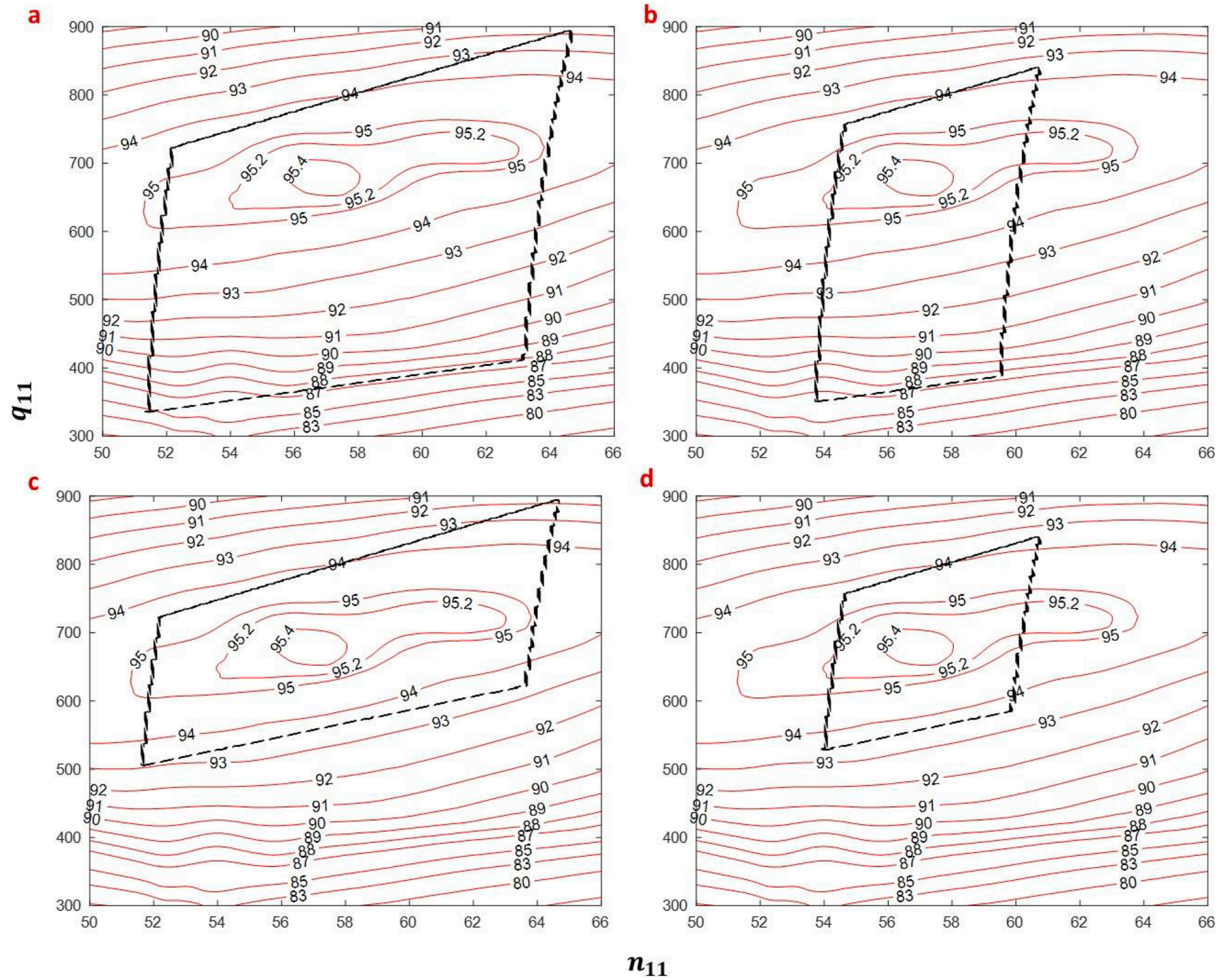


**Fig. 9.** Annual operating areas considered. a) Unit with large variation of head and load ($[0.8H_{g_{SG}}$-$1.2\,H_{g_{SG}}]$ & $[0.54Q_{SG}$-$1.16\,Q_{SG}]$) b) Unit with small variation of head and high variation load ($[0.9H_{g_{SG}}$-$1.1\,H_{g_{SG}}]$ & $[0.54Q_{SG}$-$1.16\,Q_{SG}]$) c) Unit with large variation of head and small variation of load ($[0.8H_{g_{SG}}$-$1.2\,H_{g_{SG}}]$ & $[0.8Q_{SG}$-$1.16\,Q_{SG}]$) and d) Unit with small variation of head and load ($[0.9H_{g_{SG}}$-$1.1\,H_{g_{SG}}]$ & $[0.8Q_{SG}$-$1.16\,Q_{SG}]$).

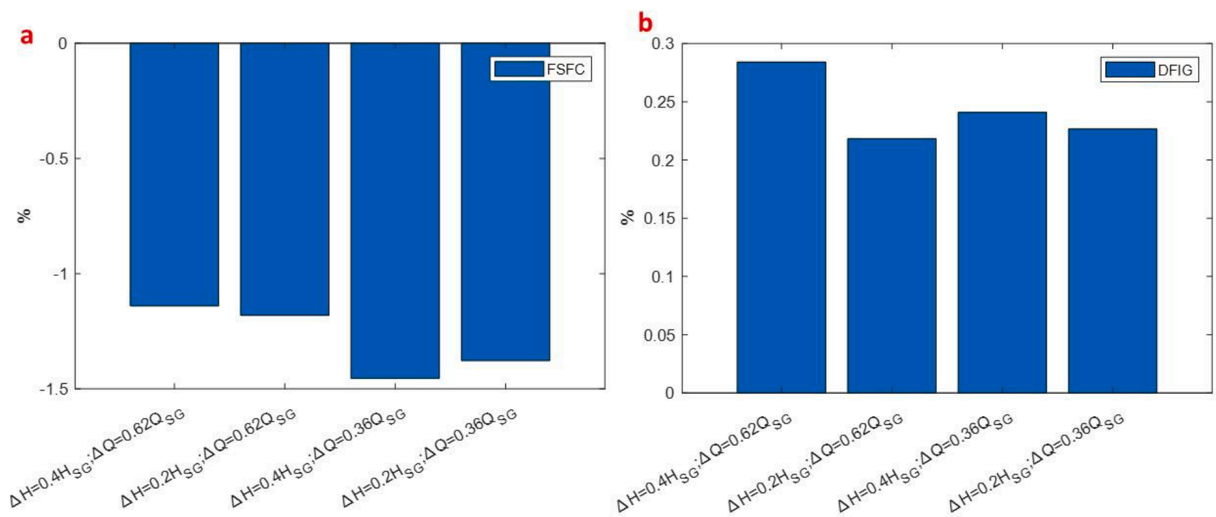


**Fig. 10.** Relative saving of water for the different scenarios represented in Fig. 9 with respect to the synchronous unit. a) FSFC and b) DFIG.

load. It is estimated that with the DFIG technology, around 0.2%-0.3% of water could be saved in one year of operation compared to the synchronous unit assuming a head variation of ± 20%. For the analyzed unit this represents 1–1.5 $hm^3$ ($1 - 1.5 \times 10^9$ liters) or 1% of the useful capacity of the dam's reservoir.

Variable speed operation may become even more interesting

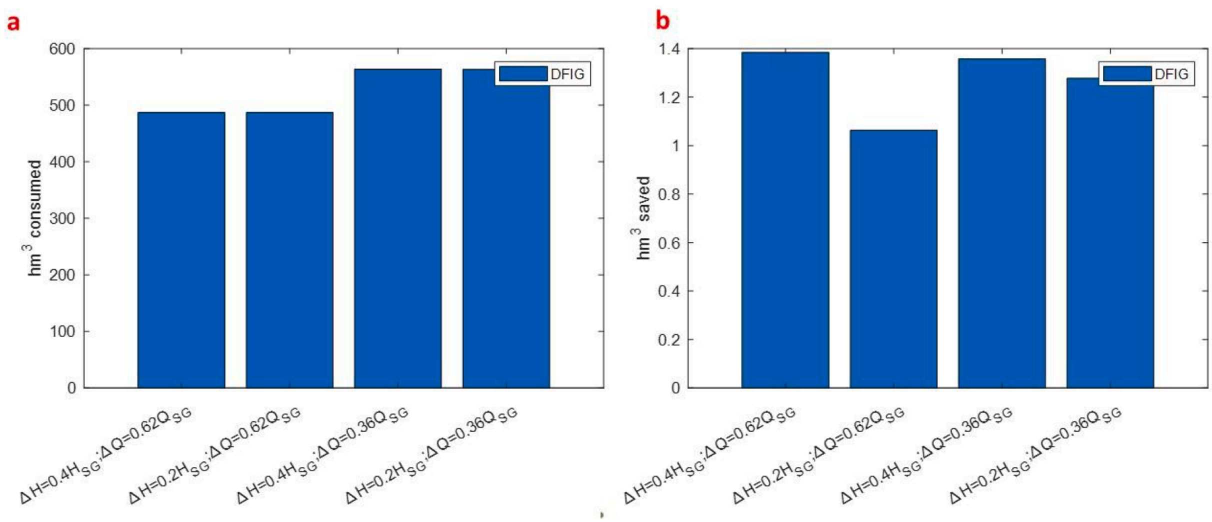


**Fig. 11.** A) water consumed ($hm^3$) in one year with the different scenarios represented in Fig. 9. b) Water saved ($hm^3$) if operating with DFIG.

considering a near future scenario with more common extreme droughts. Under such conditions, the units already installed will have to operate with heads and loads much lower than they were designed for. As seen in this study, under these operating conditions, the potentiality of saving water is maximum.

### CRediT authorship contribution statement

**Alexandre Presas:** Conceptualization, Methodology, Formal analysis. **Carme Valero:** Conceptualization, Methodology, Funding acquisition. **David Valentín:** Software. **Mònica Egusquiza:** Software. **Pedro Diogo Pinto:** Formal analysis. **Ana Gonçalves de Carvalho:** Formal analysis. **Alex Coronati:** Supervision. **Eduard Egusquiza:** Supervision.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Data will be made available on request.

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