# Conceptual design of a DOT farm generator station

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EWEA Offshore Conference 2011

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**Abstract**

The Delft Offshore Turbine (DOT) is a DUWIND research project that focuses on reducing the cost of offshore wind energy by bringing a radical change in offshore wind turbine technology. The main concept is to centralize electricity generation by having individual wind turbines create a flow of pressurized seawater to a hydropower station. The idea behind the DOT is that the high power to weight ratio from hydraulic drive systems gives the opportunity for a reduced nacelle mass and increased reliability of components by eliminating the use of individual gear trains, generators and power electronics. Therefore, the ultimate goal of this project is not only to suggest an efficient way of exploiting offshore wind but to present a cost efficient assembly.

The development of the hydraulic drive train of the individual turbines has been studied over the last 3 years. This paper builds on these results and shows the working of these systems on a wind farm level. The model is built up for a North Sea site with 5MW DOT turbines with a total installed capacity of 1GW. By investigating hydro turbines, the central hydro power station is designed and detailed in this paper.

## 1 Introduction

The DOT is a research project investigating how hydraulic transmission turbines can be introduced in offshore wind technology. The main concept is to centralize electricity generation by concentrating seawater flow from the individual DOTs. In order to conclude to the conceptual design of the DOT farm generator station, the transmission concept is defined and fundamental knowledge regarding hydro turbines is analyzed. First however, the DOT assembly is described.

It consists of a 2-bladed fixed pitch turbine, which is directly coupled to a pump in the nacelle. The pump is part of a closed loop which converts the mechanical energy of the rotor into hydraulic energy in the pressurized fluid circulating inside the loop. Hydraulic energy is then converted back into mechanical energy in a hydraulic motor at the base of the turbine. Directly coupled to the motor of the closed loop is a hydraulic pump of an open loop subsystem. This pump converts mechanical energy into hydraulic of the pressurized seawater. The accumulated and pressurized seawater flow from the individual DOTs is then pumped into a hydro power station [3].

## 2 Transmission concept of DOT farm generator station

The transmission concept of the DOT farm generator station involves hydraulic turbines directly connected to generators. Hydro turbines are used to convert the hydraulic power of the concentrated flow into mechanical power. By connecting a generator to the hydro turbine, mechanical power is then converted into electricity. A substation is defined as the combination of a hydro turbine and a generator. Several substations comprise the central generator station of the DOT farm. This concept is represented schematically in figure 1.

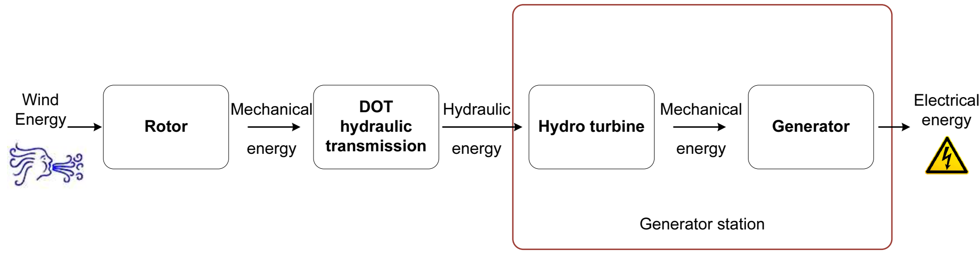


Figure 1: Schematic representation of transmission

A number of substations is required for the DOT wind farm generator station, in order to achieve high availability of the farm. In case the generator station consists of few substations, the time of full operation of the farm reduces from the O&M point of view.

The exact configuration of the DOT generator station has not yet been investigated. As far as O&M is concerned, the substations are preferable to be situated in one platform. However, no study has been performed on this aspect so far and it remains unknown if it is feasible from the manufacturing and economic aspect.

Indicatively, the DOT farm generator station is presented in figure 2.

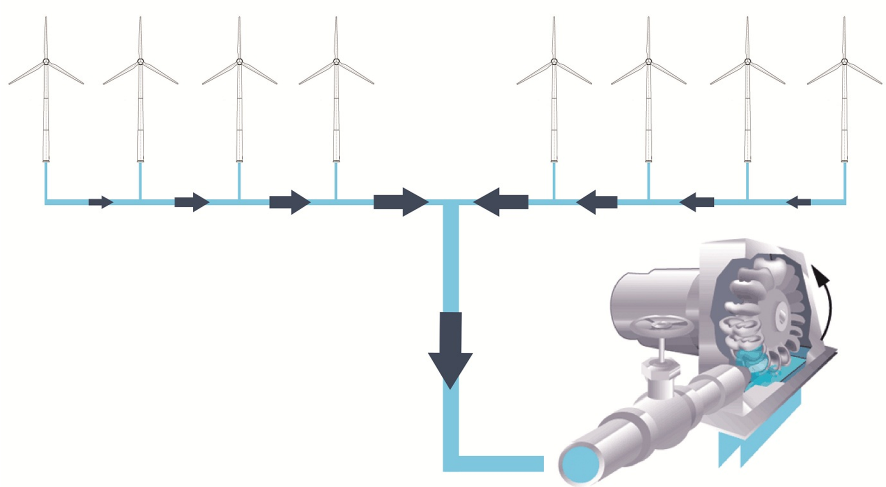

Figure 2: Transmission concept of the DOT wind farm generator station

To increase the availability of the farm and reduce maintenance costs, it is a design choice to eliminate the gearbox. Many offshore wind developers who choose to use the gearbox, face problems with it. This proves that it is not a wise choice for the offshore environment. The trend to switch to gearbox-free offshore wind turbines is supported by more and more offshore wind developers, one of them being General Electric [10]. The selection of the coupling between the hydro turbine and the generator is discussed at a later stage. To conclude the transmission concept of the DOT farm, generated electricity from all substations is transferred to a central high voltage transformer in order to connect the farm to grid. This part, however, is not further studied here.

In the coming sections, an introduction to hydro power and hydro turbines is made. The choice of the most suitable turbine for the DOT application is also discussed. Then the conceptual design of an imaginary DOT wind farm generator station with $1GW$ installed capacity is described in more detail.

# 3 Hydropower

## 3.1 Introduction to hydro turbines

The hydro turbine is the evolution of the waterwheel. Some of the most popular hydro turbines are the Francis, Pelton and Kaplan turbines, which were named after their inventors James B. Francis, Lester A. Pelton and Viktor Kaplan [6]. Schematics of these turbines are shown in figure 3.

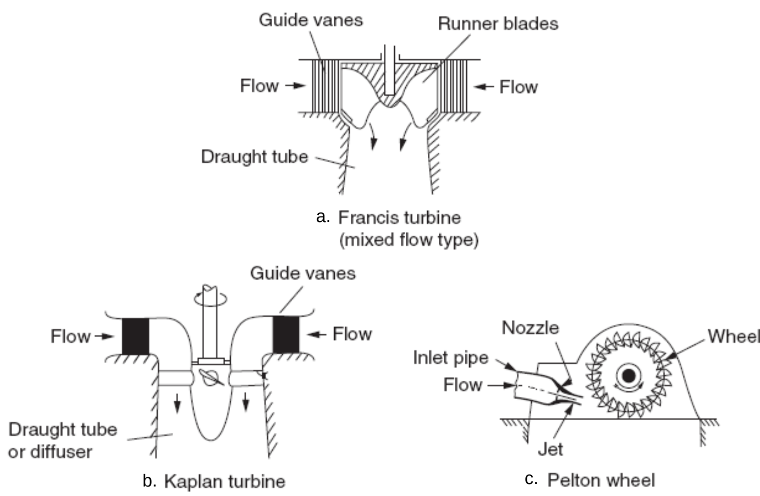


Figure 3: Schematics of hydraulic turbines [4]

All hydraulic turbines can be categorized either as impulse or as reaction turbines. This depends on whether changes in pressure are absent or present, respectively, as water flows through the turbine rotor. For instance, Francis and Kaplan turbines are classified as reaction turbines, whereas the Pelton wheel is classified as an impulse turbine. Water flow through a Francis or a Kaplan machine is characterized by variations in pressure. Their runners are fully immersed in water and the input fluid power is converted into mechanical as water rotates the turbine vanes [13]. In contrast, all pressure change in a Pelton wheel happens in one step in 1 to 6 nozzles, which guide the flow towards the buckets of the runner [4]. The Pelton runner operates in air and the hydraulic power is converted into kinetic of one or multiple water jets, which are at atmospheric pressure, and then into mechanical in the runner. Another kind of impulse turbine is the turgo turbine, which is not as widely used as the Pelton turbine [13].

Different turbines operate under different operating conditions. For example reaction turbines are typically used in low head systems with high flow, whereas impulse turbines are installed in high head systems. At this point, the term *head* needs to be explained. In hydraulic turbo machines, it is often used to measure the energy a fluid possesses per unit of weight [7]. Head is measured in $metres$, but it can also be translated into units of pressure. If the characteristics of the fluid are taken into account and head is multiplied to the specific weight, i.e. the weight per unit of volume, of the fluid, then pressure units are obtained. The term head is used more often than pressure in hydraulic engineering, however it is not easily conceived as a concept that relates the energy in an incompressible fluid to the height of an equivalent static column of a fluid. For this reason, the graphs that are presented in this work have both units to facilitate the reader.

The operating ranges for the specific speed range that characterizes them, the net head, the maximum power and optimum efficiency of current technology hydro turbines are shown in table 1. The term of specific speed mentioned is explained in the following paragraph.

| | **Pelton turbine** | **Francis turbine** | **Kaplan turbine** |
|---|---|---|---|
| **Specific speed** ($rad$) | 0.05 - 0.4 | 0.4 - 2.2 | 1.8 - 5.0 |
| **Head** ($m$) | 100 - 1770 | 20 - 900 | 6 - 70 |
| **Maximum power** ($MW$) | 500 | 800 | 300 |
| **Optimum efficiency** (%) | 90 | 95 | 94 |
| **Regulation method** | Needle valve and deflector plate | Stagger angle of guide vanes | Stagger angle of rotor blades |
| Note: Values shown in the table are only a rough guide and are subject to change | | | |

Table 1: Operating ranges of hydraulic turbines [4]

## 3.2 Flow regimes for maximum efficiency

According to Dixon and Hall [4], the definition of the efficiency of a hydro turbine is the shaft power of the turbine rotor divided by the difference between hydraulic power between inlet and outlet of the turbine. Typical efficiencies for the three most popular kinds of hydro turbines in relation to the power specific speed, $\Omega_{sp}$, are shown in figure 4.

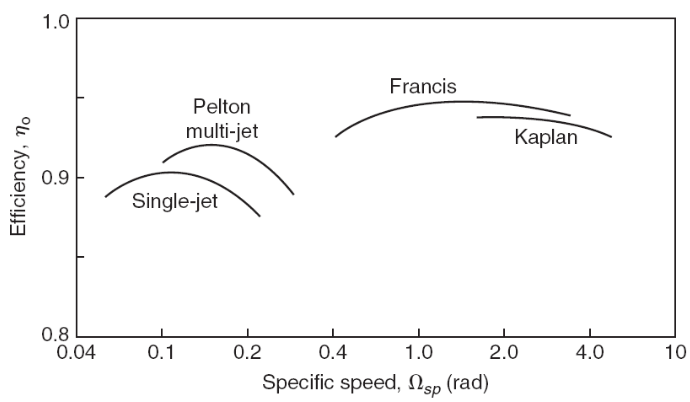


Figure 4: Typical efficiencies of Pelton, Francis and Kaplan turbines [4]

The concept of specific speed was introduced in order to help turbo machine designers decide the kind of machine that is most suitable for an application. It is a non-dimensional parameter which shows the designer the type of hydro turbine that will provide the requirement of high efficiency at the design condition.

There are two expressions describing the specific speed of a turbo machine, the specific speed $\Omega_s$ described by equation (1) and the power specific speed $\Omega_{sp}$ described by equation (2). The power specific speed $\Omega_{sp}$ is usually used for hydro turbines. Even though both expressions are dimensionless, numerical values of specific speed need to be considered as *radians* depending on the units of $\Omega$. The factors $g$ and $\rho$ are necessary for the calculation of specific speed and power specific speed in order for them to be non-dimensional. If the former are excluded, their values depend on the units employed [4].

Some key points to have in mind, helping the understanding of the specific speed concept, are addressed here. They are derived from figure 4.

- A change in the specific speed of a machine suggests that the machine design varies. This means that classes of machines are characterized by a different value of specific speed.

- If the specific speed is defined, then the machine design that gives maximum efficiency can be determined.

- Each machine type has its optimum efficiency within its own narrow range of specific speed.

$$\Omega_s = \frac{\Omega\sqrt{Q}}{(gH_n)^{3/4}} \tag{1}$$

$$\Omega_{sp} = \frac{\Omega\sqrt{P/\rho}}{(gH_n)^{5/4}} \tag{2}$$

with:

| | | |
|---|---|---|
| $\Omega_s$ | specific speed | $rad$ |
| $\Omega$ | shaft rotational speed | $rad/s$ |
| $Q$ | volumetric flow rate | $m^3/s$ |
| $g$ | gravity acceleration | $m^2/s$ |
| $H_n$ | net head at turbine entry | $m$ |
| $\Omega_{sp}$ | power specific speed | $rad$ |
| $P$ | shaft power | $W$ |
| $\rho$ | water density | $kg/m^3$ |

### 3.3 Selecting the type of hydraulic turbine for the DOT farm generator station

The DOT concept targets on high power to weight ratio for its components and therefore requires the most compact transfer of energy. In this respect, the size of the pipes transferring seawater is kept the smallest possible. To achieve this goal, highly pressurized water needs to flow through the pipes of the open loop subsystem. This requirement can be accomplished by using a type of hydro turbine that can operate at higher head, hence pressure, compared to the rest of the turbomachines. Impulse turbines are designed to do this and the Pelton turbine is the hydraulic turbine that can operate under the highest head.

Two more prerequisites for the selection of the most suitable hydro turbine for the DOT farm generator station is that it has to be efficient and of a technology that is widely used, to decrease total cost. The fact that the Pelton turbine efficiency reaches around 90% along with it being the most popular among impulse turbines, helps fulfill all the requirements; those of the most compact energy transfer without significant losses in efficiency and in low cost. Therefore, Pelton turbines are selected to be the hydro turbines of the DOT farm generator station.

### 3.4 Drive system

The drive system is used to connect the Pelton turbine to the generator. At one end, the turbine rotates at rated speed and at the other the generator rotates at the speed that generates the correct voltage and frequency. The different ways of coupling the turbine to the generator are the direct coupling, the belt coupling and the gearbox. The most efficient and reliable drive system is the first one, as it does not introduce any efficiency losses into the system. The drive systems that include belts or gears are also more prone to maintenance [2]. Having in mind that the DOT requirements are high efficiency and high reliability, the direct coupling is selected as the drive system between the Pelton turbines and the generators meant for the DOT wind farm generator station.

### 3.5 The generator

This is the component that converts the mechanical power of the turbine into electricity. Generators are essential parts of a power plant and for this reason high efficiency is required. Research on generators has progressed a lot over the years, resulting good efficiency for most modern, well fabricated generators. There are three main kinds of generators, the DC, the induction and the synchronous generator. The synchronous machine is the most widely used machine to generate power, as a consequence of its increased efficiency, adaptable power factor to high values and its relatively low cost. The typical efficiency of a synchronous generator is 95% [1]. For these reasons, synchronous generators are believed to be more suitable for the DOT farm generator station.

## 4 Conceptual design of the DOT farm generator station

In order to conceptually design the DOT farm generator station, the Pelton turbine and the synchronous generator need to be sized properly. This means matching the operation of these two with the accumulated fluid power input from the individual DOTs.

The power input depends on the wind power absorbed from each DOT, their capacity and efficiency and the number of DOTs that are connected per hydro turbine. Since the number of DOTs is chosen to be distributed evenly per hydro turbine, this is a consequence of the number of hydro turbines that are installed in the farm. The generator station is designed for a steady state. This state occurs when the DOT rotor absorbs the maximum power that it can harvest from the wind.

The DOT concept is to have a horizontal axis, two bladed, high speed rotor [8]. However, since this concept is still under research and in order to perform calculations, the rotor of a $5MW$ NREL turbine is assumed to be used. The maximum electrical output of the NREL turbine is $5MW$, which means that, for the steady state examined, there is more power than that at the shaft of the rotor due to the losses in the generator. Despite that, for ease of calculations it is assumed that this is the maximum mechanical power the rotor can obtain from the wind.

To define the hydraulic power inputted in the Pelton turbine, the DOT efficiency from rotor-to-nozzle needs to be specified. This, however, is unknown as it is also under research. An assumption for the hydraulic transmission efficiency of the DOT, 78%, can be derived by the product of rough approximations of the efficiencies of the individual components consisting it.

Another parameter that the fluid power input of a hydraulic turbine depends on is the number of DOTs that are connected per hydro turbine. This is consequently related to the number of substations in the farm. To investigate the boundaries, a minimum of 2 hydro turbines is assumed to be installed in the wind farm, because according to table 1 the maximum power output a Pelton turbine can deliver is $500MW$. On the other hand, the more substations installed, the higher the capital expenses of the farm. Therefore, the available fluid power is calculated for a maximum of 10 substations. Table 2 shows the cases that are examined further.

| Number of hydro turbines | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| Number of DOTs per hydro turbine | 100 | 67 | 50 | 40 | 33 | 29 | 25 | 22 | 20 |

Table 2: Case scenarios for DOT wind farm

Before sizing the turbine, the machine design of the Pelton turbine and its rotational speed need to be defined. The design that is chosen to be used is characterized by a power specific speed of 0.2. According to figure 4, the highest turbine efficiency, 92.5%, is reached in the range of specific speeds between 0.15 and 0.18 [4]. Since this corresponds to state-of-the-art machine design, it is expected to have the highest cost. To avoid this, the aforementioned turbine is selected, which has a slightly lower efficiency, 91%, according to the same graph.

Due to the bulkiness of the Pelton runners used for large-scale electricity generation, their rotational speed needs to be low. This makes them easier to stop in case of a grid failure, which causes the runner to rotate at runaway speed. This is not a desired situation neither for the bearings keeping the turbine in position nor for the generator connected to it as they can be seriously damaged. For this reason, synchronous generators with large number of poles are chosen. Equation (3) gives the synchronous speed of a generator connected to grid depending on the grid frequency and the number of poles. According to that, for a given frequency, the more poles a generator has, the lower its speed is. The analysis is performed for 24-, 30- and 40-pole synchronous generators directly connected to the Pelton turbines, which means that the rotational speed of both the generator and the hydro turbine is 250, 200 and 150$rpm$ respectively, since the DOT wind farm is connected to the 50$Hz$ grid of the Netherlands. This range of design speeds is considered to be normal in conventional hydro power stations [1].

$$n_{syn} = \frac{120f}{p} \tag{3}$$

with:

| | | |
|---|---|---|
| $n_{syn}$ | synchronous speed | $rpm$ |
| $f$ | grid frequency | $Hz$ |
| $p$ | number of generator poles | $-$ |

The range of the power output of each component per substation in relation to the number of hydro turbines in the DOT farm is depicted in figure 5. For the estimation of the electrical power output, the efficiency of the synchronous generators to be used is taken to be 95% [1].

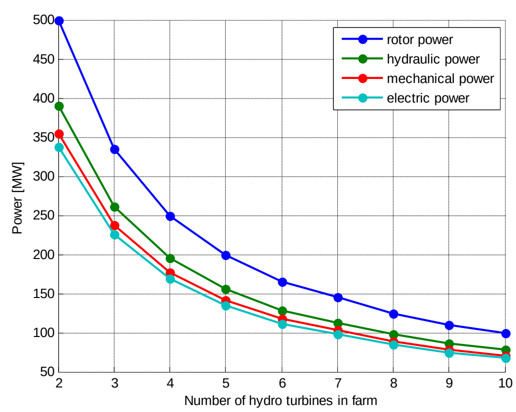


Figure 5: Power output in relation to the number of hydro turbines for $\eta_{DOT} = 78\%$

The design head and pressure are calculated using equation (2) and presented in relation to the number of hydro turbines. Based on these calculations, the flow rate required to be accumulated from the individual DOTs is also estimated. The operating conditions under which the turbine is designed to work are shown in figure 6.

Provided that the more the jets used to hit the buckets of a Pelton, the higher the efficiency of the machine, figure 4, the design is performed for a 6-jet turbine, i.e. a turbine with the maximum umber of jets. Bearing this in mind, the jet diameter is calculated using equation (4). According to empirical data it should be 12% of the PCD of the runner and one third of the width of the bucket [13]. The possible diameters of the jet and the runners are depicted in figure 7 in relation to the number of hydro turbines in the farm. It is mentioned here that in order not to get involved with the detailed design of the nozzles or the spear valves, the calculations are performed only for the diameter of the jets.

Having estimated the size of the Pelton turbines of the DOT farm, the size of the generators to be connected to them remains to be approximated. To do that the concept of the Lorentz force density is used. According to fundamental electromagnetism, the Lorentz force is the force applied on a moving particle of charge through electromagnetic fields [5]. When large numbers of charged particles are in motion, i.e. in electric generators, the term of force density is used to describe the Lorentz force per unit of volume. The force density ranges between 25-50$kN/m^3$, depending on how good is the manufacturing of the generator, however a typical value in current technology generators is $44kN/m^3$. The size of the synchronous generators is therefore estimated by equation (5) [11].

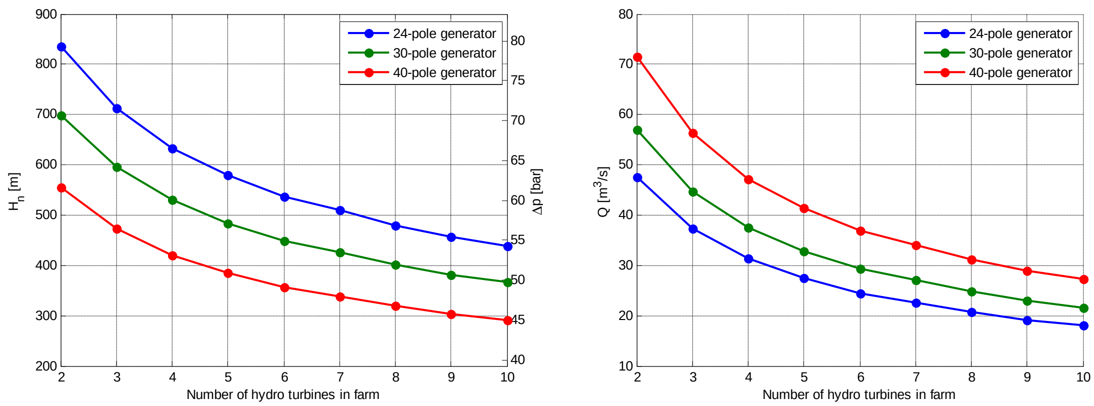


Figure 6: Operating conditions in relation to the number of hydro turbines for $\eta_{DOT} = 78\%$

$$Q = A_{jet} \cdot v_{jet} \cdot n_{jet} = \frac{\pi D_{jet}^2}{4} \cdot v_{jet} \cdot n_{jet} \tag{4}$$

with

| | | |
|---|---|---|
| $Q$ | volumetric flow rate | $m^3/s$ |
| $A_{jet}$ | cross-sectional area of the jet | $m^3$ |
| $n_{jet}$ | number of jets | $-$ |
| $D_{jet}$ | diameter of jets | $m$ |

$$P_{mech} = 2\omega_m \cdot V_r \cdot F_d \tag{5}$$

with:

| | | |
|---|---|---|
| $P_{mech}$ | mechanical power input | $W$ |
| $\omega_m$ | angular velocity of shaft | $rad/s$ |
| $V_r$ | generator rotor volume | $m^3$ |
| $F_d$ | force density | $N/m^3$ |

The volume of the generator rotor in relation to the number of hydro turbines in the farm is calculated for the case of the three different pole synchronous generators. This is shown in figure 7.

For the completion of the design, some assumptions need to be made, as the analysis depends so far on the number of hydro turbines in the farm and the number of poles, hence the design speed, of the generator.

As far as the number of substations in the farm are concerned, this depends on two parameters, the availability of the farm and the amount it costs to have them. The availability of the wind farm clearly increases as the number of hydro turbines increases, however at the same time the total cost of the wind farm also increases. Due to the fact that no further research is performed on the exact influence of these two parameters, as only the conceptual design of the farm is examined, the number of Peltons that gives the best combination of farm availability and low cost is only assumed theoretically. Five substations are considered to be a realistic number, which is assumed to keep the cost low and the availability high.

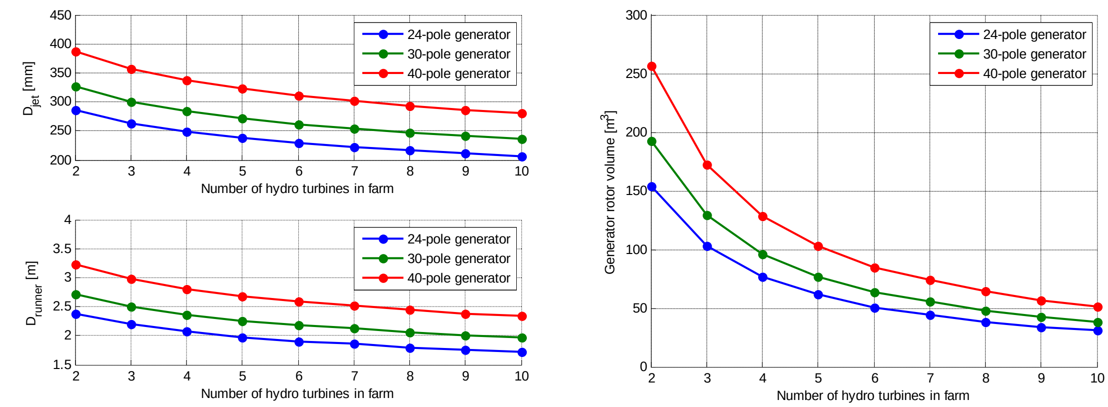


Figure 7: Sizing of Pelton turbine and generator in relation to the number of hydro turbines for $\eta_{DOT} = 78\%$

From figures 6 and 7, it is concluded that the design rotational speed influences the operating conditions and the sizing of both the hydro turbine and the generator significantly. Given that the DOT concept targets on operating at high pressure, it is derived from figure 6, that the generator operating at higher speed is the most suitable from the ones examined. This means that a 24-pole synchronous generator is coupled to each hydro turbine.

Taking into account these assumptions, the conceptual design of the DOT farm generator station is finalized. The farm consists of 5 6-jet Pelton turbines and 5 24-pole synchronous generators. Each hydro turbine operates at $579.1m$ head, i.e. $56.8bar$, with $27.5m^3/s$ flow rate, rotating at $250rpm$ and providing $142MW$ of shaft power. The PCD of each runner is $2m$, the diameter of each jet is $237mm$ and the width of the buckets is $712mm$. The number of the buckets per Pelton turbine depends on the detailed design of the bucket, and is therefore not determined.

Moreover, the rotor volume of each synchronous generator is approximately $62m^3$. A relevant conclusion regarding the size of the hydro power generator is that it is much smaller than the size of a conventional wind turbine generator due to the fact that it can rotate at higher speed. Indicatively, the volume of the electrical station of the direct drive Mervento 3.6-118 wind turbine rotating at $14.1rpm$ is approximately $220m^3$ [9].

# 5 Conclusions

Pelton turbines are the most suitable hydro turbines that apply to the DOT concept. Since high power to weight ratio is a target for the DOT farm components, the most compact transfer of power is desired, hence high pressure operation is required.

The specific speed of a hydro turbine is essential for the selection of the most appropriate turbine for a specific application and the determination of the operating conditions under which it works. Moreover, in case the specific speed of a machine changes, then the machine design is not the same. Different types of machines are characterized by a different value of specific speed and each machine type has its optimum efficiency within its own narrow range of specific speed. Once this characteristic value is defined, then the machine design that gives maximum efficiency can be determined.

As far as the drive system is concerned, high efficiency, low maintainability and high availability of the farm are prerequisites. This is achieved by coupling the Pelton turbine directly to the generator and for this reason this drive is more preferable than the gearbox or the belt coupling.

The synchronous generator is the most popular machine that generates power, which at the same time has the highest efficiency, over 95%. If the adaptable power factor to high values and its relatively low cost are added to that the selection of the synchronous generator for the DOT farm generator station is justified.

For a specific machine design of a Pelton turbine, characterized by $\Omega_{sp} = 0.2$, the operating conditions and the size of both the turbine and the generator can be estimated. In the case of 5 substations consisting the generator station and 78% being the efficiency of the DOT, the farm comprises of 5 6-jet Pelton turbines and 5 24-pole synchronous generators directly connected to each other. Each hydro turbine operates at $579.1m$ head, i.e. $56.8bar$, with $27.5m^3/s$ flow rate, rotating at $250rpm$ and providing $142MW$ of shaft power. The PCD of each runner is $2m$, the diameter of each jet is $237mm$ and the width of the buckets is $712mm$. Moreover, the rotor volume of each synchronous generator is approximately $62m^3$.

This leads to a conclusion regarding the generator volume. The size of the generator of a hydro power plant can be smaller than the size of the generator directly mounted to a wind turbine. Indicatively, the volume of the electrical station of the direct drive Mervento 3.6-118 wind turbine rotating at $14.1rpm$ is approximately $220m^3$ [9]. The difference in the generator size lies on the fact that the average rotational speed of the hydro turbine is higher than the rotational speed of a wind turbine as an average. Typical values of wind turbine rotational speed are between 10 to $22rpm$ [12], whereas a Pelton turbine usually operates at a few hundred *rpms* [1].

Apart from the generator size, the design rotational speed of the hydro turbine influences the operating conditions significantly. Given that the DOT concept targets on operating at high pressure, it is derived, that a generator operating at higher speed results a turbine design which can operate under the preferable conditions.

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