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Controllo di un sistema PAT (Pump as Turbine)

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An insight in basic control possibilities for "Pump As Turbine" systems

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un Grazie speciale a Dani,
per avermi avviato al mondo delle PAT,
per l'accoglienza dublinese,
e per tutto il supporto che mi ha saputo dare
per scrivere queste righe.
chapeau!

0.1 Abstract

0.1.1 English

This paper works on the theme of the control of a **pump as turbine system (PAT)**. The idea is using a classic radial pump, reverse it, and using it to produce electricity, as if it was a turbine. Exactly as when using, as happens also in thiS case, a motor as a generator: the same machine, the opposite power direction. Why? to produce clean and renewable energy. Or better to **recover energy**, that's saying producing a even more positive effect: is not about placing our wind turbine at the tp of a hill, is placing a rude pump at the end of an industrial process, to recover eenrgy that otherwise will be thrown away. The result is to reduce the overall energy consumption of whatever plant.

Nowadays, in a world growing in population and in energy hunger, we do have to invest a lot in such solutions. If we want to have energy for everybody, we can not just imagine to produce more, we have to start thinking how to **reduce consumption**. Recovering here means getting back in electricity some energy we had already spent (eg: to pressurize a water distribution system (WDS) through the use of pumps), or just producing power in situation that could allow it, and where at the moment this energy is dissipated (once again a WDS pressurized by gravity where pressure exceeds). So is talking of a technology that reuses, without limiting the functionality of the processes up and downwards. Is placing a component in a system that allows us to get clean and free energy from an **already existing process**.
The *first part* of the work goes in exploring the functionality and possibilities for the pats.

With today technology we can add even more flexibility, thanks to power electronics going cheaper, and allowing us to play with the drive control and the different **speed regulation**. So is matching of last generation power electronics with the reliability of the workhorses of mechanical engineering, that are the pump and the induction motor.
Practically the use of the machine "pump" as a turbine, make arise some issues that a designer has to deal with, since its behaviour is not that easy to predict. The *second part* this work deal with these theme of **modelling**. Also different actuators have to be coordinated at the same time to maximize power production: this is the task in the *last part*, where a **control logic** is developed and implemented and an example of system is **simulated**.

0.1.2 Spanish

Este trabajo va sobre el tema de las **bombas como turbinas** (Pump As a Turbine). La idea es la de utilizar una bomba radial, ponerla al revés, y aprovechar de esta para producir electricidad, como si fuera una turbina. Es lo mismo que pasa con un motor cuando se utiliza como generador: la misma maquina, un opuesto flujo y potencia.
¿Porqué meterse en este? Para producir energía limpia y barata, o mejor, para recuperar energía. Este es todavia mejor que producirla: no es ponerse en la cumbre de una colina bonita y disfrutar del mejor viento, sino ponerse al fundo de un proceso y **recuperar la energía** que se queda en un fluido, y que de otra forma sería tirada a la basura. El resultado de todo esto es una producción de electricidad y también una mejora de la eficiencia global de la planta.
Al día de hoy, en un mundo donde la población sigue creciendo y el hambre de energía con esa, invertir in tecnologías como esta es muy importante. Si queremos energía para todos, producir mas no puede ser la única respuesta, tenemos que empezar a consumir menos. Recuperar parte de la energía que hemos gastado ya para un proceso (como en caso de un acueducto presurizado por bombas) o energía que ya existe (un acueducto presurizado por gravedad) sin quitar funcionalidad al proceso, ni consumir otro combustible o impactar en el medio ambiente de alguna forma, esta es la idea. En la *primera parte* del trabajo, entonces, el funcionamiento de las pats es presentado, con una panorámica en sus posibles aplicaciones.

Si a todo eso le juntamos los progresos en la electrónica de potencia, que sale cada dia mas barata, accesible y fiable, podemos construir un sistema todavía mas flexible: controlar el motor con un accionamiento de **velocidad variable** nos permite gestionar mucho mejor el sistema. estamos juntando dos puntos de fuerza de la ingenierìa como el motor de inducción y la bomba, con la mas reciente tecnología en ámbito de electrónica de potencia.
Desde el punto de vista practico el control de la bomba como turbina tiene que ser estudiado por su cuenta, como se necesita un modelo diferente. A este tema es dedicada una parte del documento, o sea al desarrollo de un modelo funcional al control. También hay que coordinar los varios agentes para que el sistema se porte como debe y se produzca potencia. Sobre esto va el *apartado central*: desarrollar una lógica de control para diferentes situaciones: se intenta escribir un control que permita disfrutar del sistema en la mejor manera. Al *final* un modelo es creado en Simulink y unas **simulaciones** de una situación símil-real son presentadas.

0.1.3 Italian

La presente tesi si propone di realizzare uno studio sulla possibilità di controllo in sistemi di PAT, Pump as Turbine: questi impianti, di non recente scoperta, si propongono di utilizzare delle comuni pompe centrifughe come generatori idraulici di corrente, semplicemente invertendo la direzione del flusso.
Tale tecnologia è tornata alla ribalta negli ultimi tempi nell'ottica dello sviluppo di tecnologie per il **recupero di energia** e di produzione distribuita: permette infatti di ridurre parecchio i costi di investimento e ottenere un generatore di energia rinnovabile installabile sia su corsi d'acqua con portate ridotte, che in processi industriali dove serve una **regolazione o dissipazione di pressione**.
In particolare il costo ridotto della pompa rispetto alla turbina fa la parte del leone nella riduzione di costo, ma a questo si accompagna sicuramente lo sviluppo recente e rapido della tecnologia di conversione **elettronica di potenza**, che ha portato ad avere inverter commerciali con ottimi algoritmi di controllo interno a prezzi decisamente più competitivi rispetto a qualche decennio fa, quando le prime PAT venivano installate in zone rurali.
Questo ha aperto la strada all'idea del **controllo, variando la velocità e il flusso,** che può essere la soluzione verso una **maggiore efficienza** per questi impianti che si trovano a lavorare spesso in condizioni difficili e che al contempo hanno una zona di lavoro di massima efficienza molto ridotta.
Ecco quindi l'idea di provare a investigare le possibili logiche di controllo di questo ipo di sistemi, con l'idea in testa sempre solida di non snaturare l'impianto con controlli costosi e ocmplessi che ne compromettessero **semplicità e affidabilità**.
Il lavoro, in ultima istanza, si propone un'introduzione sui sistemi PAT e sul loro funzionamento, essenziale per arrivare, poi, a elaborare una logica di controllo, con la sua filosofia e la sua matematica. Da questa si passa poi all'implementazione in ambiente virtuale e alla **simulazione** di un caso reale in Simulink.

Chapter 1

Introduction

this master thesis tries to have a look inside the world of the energy recovery from pumps used as a turbines, PATs, from the point of view of the control systems. few different way of controlling a pat are studied, discussing its convenience and feasibility in different situation. finally a simple proposal of control application is developed and tested in Simulink.

a well known tech with new eyes for sure pumps are not a "new" technology, and their use to produce electricity as always been known and there are really interesting studies about that go back to over 40 years (e.g. Paul Garay's article on Hydro Review [6]). but the spread in using pats never happened and they were something concerned to little isolated plants in rural systems, used as a poor alternative just where the grid could not arrive. lastly, instead, thanks also to the rise of energy need, in a world that keeps growing in population and in the consumption of resources, they have been coming back to attention.
studying pats nowadays means looking at a well developed technology with the perspective of who has different weapons: the cheap and everyday used power and micro electronics. the actual interest on this way of electricity production, at the end, rely on this:

1. pumps are cheap, well known and really reliable;

2. but also they can produce electricity basically without any structural modification, just turning it around and changing the flow direction;

3. and they can also serve, at the same time, for other purposes than that of producing electricity.

is saying: i can put a pump in a process e.g. to regulate a flux, and ending with my process working well but not only: i can also produce power, without other elements than the one i needed for my regulation. this led to the possibility of creating win win situations where the power production becomes almost a secondary (but really interesting and useful) effect, that could help to lower the investment cost and increase the overall efficiency, of whichever system.

environmental concerning and it is not only about the money. even if it is clear that the low cost of pumps is the key of this technology, at the same time we do have to remember that every Joule produced in renewable way has also a big value in environmental terms. this could make a clean energy production system even more competitive. in case of pat we can either talk, depending of situations, but of reducing consumption (e.g. in case of a water distribution system when to manage it well you have to spend energy that you can in part recover with a pat at the end of the distribution) or of renewable energy production (e.g. in case of little hydropower systems).

work in progress so why this systems are not that used? what at first was slowing the spread of this technology was for sure the higher cost of power electronics, that has started decreasing only in recent years ad is still the main voice in terms of costs for a pat installation. another thing that has to be accounted in the frictions against the diffusion of pats is the difficulty in finding good information about the pump behaviour in turbine mode, since the producers usually do not provide neither compute this ones. more or less recently though, several studies have been carried out on this direction, and experimental results are slowly piling up, starting to create a quite accurate bibliography on this.
is exactly starting from these informations that this work tries to explore a bit the possibilities, in terms of applications, offered by this systems.

to sum up the idea of the work was then that of exploring the limits, in some applications, of a basic control method. following the main line of projecting a control for a real case study, looking then at the others possibilities offered by a controlled PAT: with or without electrical variable speed regulation (ER); with or without, (and when it is possible), the series throttling valve and the hydraulic only regulation (HR); systems with backwards pressure and or flow requirements; with different size pump in parallel.

methodology in order to try to match the objective just stated work has been organised as follow:

1. a general introduction to hydropower production, to PATs world and idea and its potentials applications;
2. a look on method and the math model used;
3. a look to a typical installation, its components, how they works and what they do;
4. the work itself: going a bit deeper in the machine, trying to elaborate a logic for controlling it in the best manner. some different cases are discussed, supposed to be the most common and useful. few simple examples application of the developed logic are proposed and testes in a virtual simulation environment (Simulink);
5. an overall look to the work and conclusion;

Chapter 2

Micro hydro power

2.1 what we are talking about

hydropower production is basically a way of generating electricity converting the mechanical energy of a fluid through an electromechanical converter, composed by a turbine and an electric motor. man has has always looked at water as one of the easiest way to get energy, since the water cycle, fed by the sun, works on his own. the hydropower sector has been studied a lot and, from the firs watermills many improvements have been made and plants have been constructed, in order to provide energy for the everyday needs of humanity. but why going micro?
basically the idea in the whole XXth century had been that of trying to build bigger and bigger plants: from the economic point of view it was generally profitable, had higher efficiencies and less plants could serve for satisfying energy demand. [30] but now, thinking about Europe, two main factors pulls towards going little:
-a environmental concerning is growing about the effects on the environment of this kind of big plants, that affects strongly the place where are built, changing it forever, in terms of landscape but especially when modifying the ecosystem of usually really sensitive places, such as the mountain environment where usually big hydropower plants have to be placed.
-there is actually almost no place left for new big plants.
at the same time the world goes on with his hunger for energy and this process will need quite a long time to reach an equilibrium. and if before the solution to feed it were in terms of burning fossil fuels, today that is luckily no more possible thanks to a major attention of the public for the effects of this on environment. so solution are needed and water remains a really interesting one.[33]

the latest development of the sector are in the direction of not limiting the hydropower energy production to free water running, but extend it to to energy recovery.
here is where the PATs systems play the game better: even if they could be perfectly used as a cheap and reliable solution also in classic microhydropower, and could be considered as a valid solution also in this field, they are especially suitable for application of energy recovery, where high reliability and low cost are usually the key terms of selection.

why micro? , can't pat be used alternatively to big turbines? in terms of dimensions and power productions on the market we can find pumps of every dimensions and power, but not all are suitable for be used in turbine mode and how to chose a pump to be used as a pat has been object of different studies [2] and will be discussed a bit in the next chapter. but the key point regarding the sizing of a PAT plant is the efficiency: if we are going to build a big power plant with the objective of producing electricity, then we will design the system in specific way to get the better efficiency, and we will choose a machine that fits perfetly teh requirements of the system. in this case traditional turbines are for sure the good choice and will provide higher overall production.

pumped energy: a competitor? another case in which a pat could be an idea, but usually is not suitable are the traditional pumping systems used in electric distribution/transmission systems as an energy storage. in facts if a plant is constructed with this specific purpose will be designed to maximize the round trip efficiency (that for the last constructed systems is around 70/80% [34]) and the election of the perfect machine will probably exclude the pats in favour of a Francis turbine (even if this should e evalued case by case and whenever the two technology would overlap, eg in a little water storage system, PATs system could be an interesting solution given the really lower cost of a pump compared with a Francis turbine [35]).

how small? finally the idea of PATs (even if for sure, they can be used wherever one should need them) is then placing turbines in situations suitable for energy recovery from already existing systems, maybe built and working with other objective than that of producing electricity or from energy reduction with low power potential. talking about power and scales the idea is that going bigger the cost/kWh becomes cheaper and cheaper[8], but at the same time this trend crashes with what just said about going smaller. so at the end is really difficult to define a range of use for pats but we can really approximately say, to give the reader an idea, that could be considered within 1kW and 2/300kW.

Table 1 Hydroelectric capacity applications from small-scale categories

Hydropower category	Capacity in power output	Potential hydropower use either as a single source or in a hybrid configuration with other renewable energies
Pico	Up to 20 kW	10 kW network to supply a few domestic dwellings
Micro	20 kW to 100 kW	100 kW network to supply small community with commercial/ manufacturing enterprises
Mini	100 kW to 1 MW	1 MW plant can offset about 150 000 tons of CO_2 annually and will provide about 1 000 suburban households with reliable electricity supply
Small	1 MW to 10 MW	1 MW to 10 MW network – electrical distributions will be at medium voltage ranging from 11 to 33 kV and transformers are normally needed; the generation must be synchronised with the grid frequencies (typically to 50 or 60 Hertz)
NB: All installations above 10 MW are classified as macro (or large) hydropower plants		

Figure 2.1: a comparison in small hydropower sizes, (from http://www.scielo.org.za/img/revistas/jsaice/v56n3/01t01.jpg)

2.2 possible application of PATs

but which are the possible scenarios where to place a pat? are there really possibilities for them? well different situations can be individuated as suitable and some examples of installation have started to appear in the lasts years. the truth is many of them where conceived more as experiments than as standard installation, but this has led to interesting and different applications, and usually the results were positive, with good efficiencies and reliability of the systems. some examples of possible applications are described below to give an idea of the typical background for a PAT installation.

water distribution systems the most important player in the game of offering possible pat applications is for sure the water distribution system (WDS), as different studies state [9], [2] [8]. water is essential to life and, even if in our curious world, is it real that still exists countries in which it is not like this, having a fresh water service providing it at home whenever we want is quite common, al least in the firstly developed country. this makes the water distributions systems one of the most widely extended and most developed grid in the world. managing a water grid is a complex problem, and in order to provide all the users water at the right pressure many times they have to reach higher pressure than the one needed by many users. as can see in figure one example of this situation is the different pressure needed by industrial costumers, that's higher than the one for simple civil usage. these kind of situation create the first and maybe most common case of overpressure that has to be created (and paid in terms of energy and money) and that at the end exceeds.

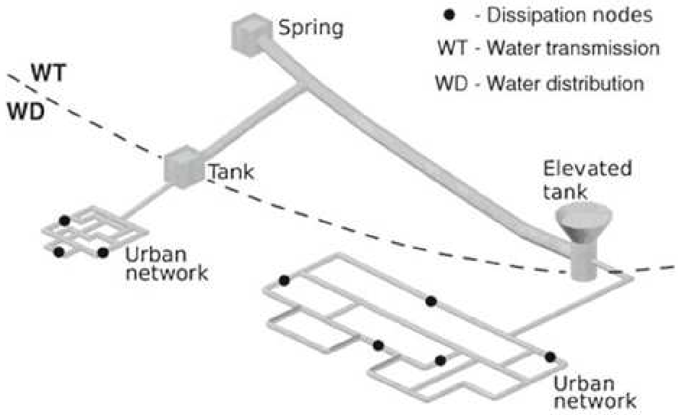

Figure 2.2: water level distribution and possible nodes with overpressures. [1]

localizing the places in which this situation happens is not that easy, but studies are being carried on this topic another circumstance in which a WDS could fit for a PAT system could be a node of the system, or the presence of a tower (or without tower too) storage tank. in case of tower tank the pressure of the inlet flow is for sure higher than the height of the level, and this is an overpressure that usually gets dissipated . also in case of water basins and storage not in tower but not in pressure we have the same case of inlet flow with an energy that will be, for most part, thrown away, usually with a pressure reducing valve (PRV). substituting a PRV with a pat is one of the most promising applications case (the two situation were studied by [8]).

WasteWaterSystems remaining close to the WDS, there are interesting locations for PATs in the wastewater sector: not only the possibility to generate from the direct flow of used water in thse cases where water has an energy charge: e.g. rainfall water collected on rooftops, or just discharge water from all the processes taking places at some higher level: could this be the case of a building with the washing-machine on the higher floor, or of some houses placed higher on a mountain with respect to the waste treatment plant (WTP). and then for sure the water treated from the WTP, that is normally thrown away to the nearest river, but sometimes there could be a gap in height between the two that could be turbined. this is the case of the plant of Five Fords in Galles, where with the Dŵr Uisce programme, a pilot plant is being designed.

irrigation systems water is important to man not only for his own necessity, but also for agriculture: the first big basins are constructed and managed in order to satisfy the water need of this sector. and this is a parallel grid that has a big potential since it has all the characteristics of the already discussed WDS. traditionally water distribution systems for irrigation purposes were designed more likely with open channels and low gradients inclinations, to be managed just with hydrostatic pressure. but recently, in order to reduce the amount of water evaporating from open channels in sunny days, that is a major requirement in dry areas the tendency is to move to pressurized systems, as is happening in andalucia. [**?**]. this means more energy to pressurize, and the idea of recovery some og this is for sure really interesting: a newly designed system could integrate pats from the beginning and these could help manage the whole grid. in literature different references report the use of pat in irrigation systems (e.g. [6] or [2]) and studies on variable speed control in his secotr exist too [15].

salt water even if there seem not to be existing projects of this kind using pats, also this sector could be interesting for pats. there are examples of profitability of pat in the desalinisation processes [3], but their characteristics suggest they could fit also for other pursposes, such as salt water pumped energy storage: a pat has less requirements on the fluid processed [26] than the majority of turbines and can pump, for sure. the idea of sea water storage is everyday more important, given the rise of unpredictable sources power installed, and plants using pumped sea water are being constructed [28] [27] [29]

industrial processes staying close to the WDS, we find all this industrial plants that (usually linked to the public WDS) needs water for their processes. water is usually taken, pressurized if needed, or at least pumped just in order to make it move, used, and then have to be treated before being thrown back to the system. is it very common that in doing this some possibilities of energy recovery happens: some studies on this localized as promising different industrial sectors: from the mining and oil and gas, to pulp and paper industry, to chemical industries [3], [2]

microhydro last but not least is the option of using a pat just to produce electricity from running water. a pat system is a cheap and reliable apparatus that could fit the exigences of electricity of a little power consumer, more likely isolated from the grid but also connected: in the first case there will be the possibility to use the pat without a precise control and the power electronics apparatus, that will make the whole thing simpler and cheaper, with the consequent poorer quality of the power; in the second case the power electronics will be quite essential, with its cost, but it is likely that this will still result competitive with the other option (such as, e.g. a little pelton). for the specific purpose of producing power to be sold to the grid distributor also a pat could be considered as an option but in that case it may be better a turbine in order to take profit of all the possible energy.

2.3 the need for a control

such a variety of feasible application suggest us how different could be the system in which a pat could be placed, and so we can imagine how much could vary the constraints this system will impose on our turbine. or better, how much flexibility will it need to be suitable and appealing to be installed in such diversified circumstances.
and how we can provide flexibility? for sure controlling it is a way. a proper control, that has to deal with the opposite characteristic of low cost and reliability, could make a pat much more appealing:
-first of all extending its working range: a variable speed control makes it possible to work with higher and slower flows and pressures;
-then making it behave in a controlled way, is to say making it an alternative (and not one addition, with consequent much manteinance) to another kind of actuator in order to reduce or regulate a pression or a flow in the desired way, as could be for a pressure valve, as said;
-making the apparatus working automatically, and making its behaviour programmable according with the system constraints and specifications, and with the turbines characteristics;
-increasing the performance of the system: thinking about a flow control, for example, a closed-loop flow control will ensure a way higher precision than, for example, a simple throttling valve.

substituting an already existing equipment with a controlled pat could so offer not only the advantage of the electricity production, but also an improvement of other aspects of the system and its general efficiency and functionality.

resumen of benefits and drawbacks:

advantages	**drawbacks**
extended range of operation	need for power electronic: cost and dimension
automation of the process	in case of substituting a simple valve: quite higher investment cost
more overall flexibility	not easy to find dedicated control on the market
possibility of regulation (of flow or pressures)	
energy saving and production	
low maintenance due to reliability of components	
low investment cost compared to a turbine	

Dwr Uisce Programme DUP is part of the Ireland-Wales 2014-2200 programme, a cooperation project that aims to "work together to address common economic, environmental and social challenges", with the contribution of EU funds. the DUP is part of this big programme and is collaboration between the Trinity College of Dublin and the Bangor University (Bangor is a little (16358 inhabitants) city in the north west of Galles); it focuses on the suitability of the WDS for innovation developing new low carbon energy-saving technology. in this frame studies on PATs are being carried, with a pair of pilots installation in programme for construction in the next years, both in ireland and wales. the programme is wider and also the aspect of energy recuperation from waste-water system is being investigated.

Chapter 3

Pumps As Turbines

3.1 pump as turbines, an introduction

after we have seen many of the feasible situations where to install a pat, we go to the point. what is a pat? a pat is a pump mounted in the reverse manner as for pumping. inverting the inlet and the outlet, the same machine switches from being an electrical to mechanical converter (motor) to its opposite: an electro-mechanical generator.

and the good thing is that, with the majority of the suitable pumps, we can do this without changing absolutely anything: a good election is sufficient and we got a turbine for the cost of a pump. for sure there are different investigations as the work made by Alatorre-Frenk [2] or Chapallaz's manual [3] that proved that little modifications (on the impeller or on the vane, various) could improve a bit the performance, but what is fine is that is not essential.
not all the pumps are suitable for working in turbine mode, there are different studies on this (e.g.[2] or [3]), with a lot of experiments conducted with different pumps and the bests have resulted to be the centrifugal ones. are there different theories also on how to elect the perfect pat, that will briefly discussed later on.

choosing a pat? but why it is so difficult to choose a pat? basically since there is not, still, one reference mathematical model to study the behaviour of an object, the pump, designed for another task (moving water up), working in turbine mode. and even if nowadays, searching a bit, we can find on the market machines precisely designed for this purpose, normally

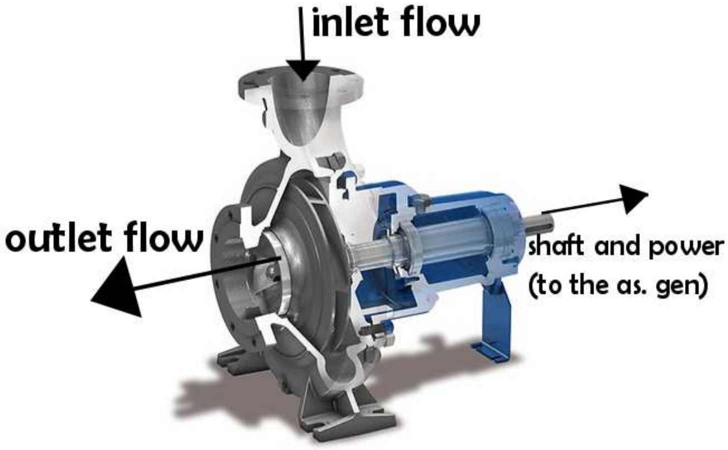

Figure 3.1: flow direction in a pump used as a turbine. modified from https://www.ksb.com/image/131866/17x11/650/421/c5e92cc15803a63c80212b66c9675222/n schnittbild.jpg

the pump producer does not test his pump this way. so the idea has usually been trying to use the classic turbo-machinery theory that will be introduced afterwards.

doubleface but lets go back to the operation of reversing the direction of flow: how we can see in the 3.2 the four quadrants diagram for a pump is quite complex since it is not just about the direction of flow: to produce power we need torque and speed in the same direction, that's say from up to down, following gravity. and the only possibility is to work in the marked area. it is to say that there is also another potentially interesting area for our study: the little slice called D in the diagram. cases could happen in which for some reasons (eg to fit system constraints, will be discussed lately better), we can decide to go to work here. for example with the system demanding torque (e.g. is the case of low head and high flow) we can decide to give power to the system, maybe to force a desired flow or head; but we will see this better when talking of power and torques.

3.1.1 curves

how a pump works? is from this question that we have to start a study on pat. the main curve to study a pump behaviour is the Q-H curve, and it will be the same for studying it in turbine mode. the Q-H curve show us how the specific pump we are dealing with works, so it is different for every machine.

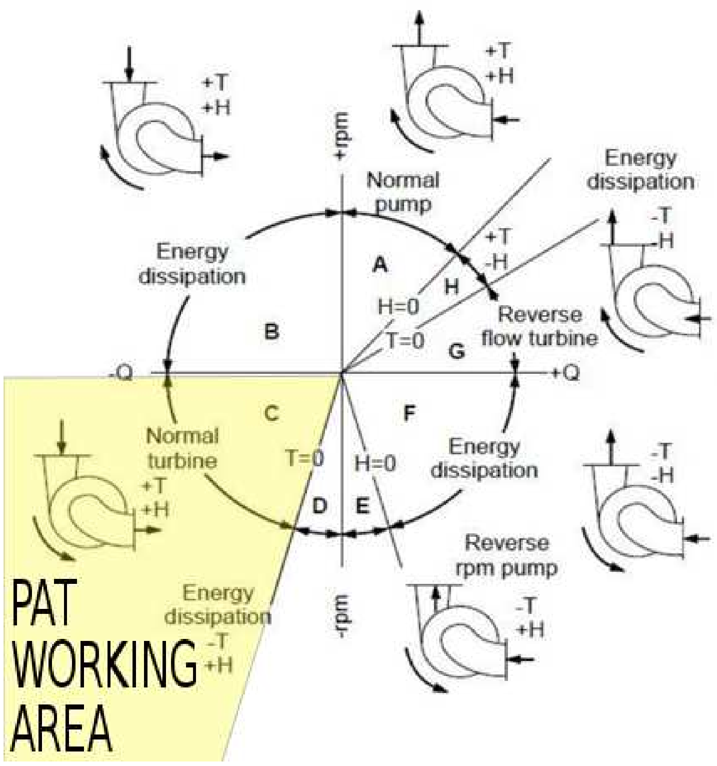

Figure 3.2: pump torque-speed operation diagram, adapted from (BAUMGARTEN, ET AL., 2005)

it shows, for a given power, how flow and head vary: as predictable with low flow we can reach higher head. this curve changes radically when in turbine mode: the flow and head will still influence the system, and usually the head will be determined by the external conditions (probably the height of the basin, or the pressure of the inlet flow), and the flow will follow.

BP it could be useful introduce another concept that we will need later: that of BackPressure (BP). the backpressure is simply the pressure required at the outlet of the installation, by the system and the downstream processes. how can we visualize it on the qh plane? in case there is a BP to be taken into account the available pressure head reduces basically to the difference between the total head of the inlet flow and the BP. so we can imagine the horizontal axe to move upwards to the BP value: we can go on working with our qh graph, but we will work basically with head difference and not with absolute values.

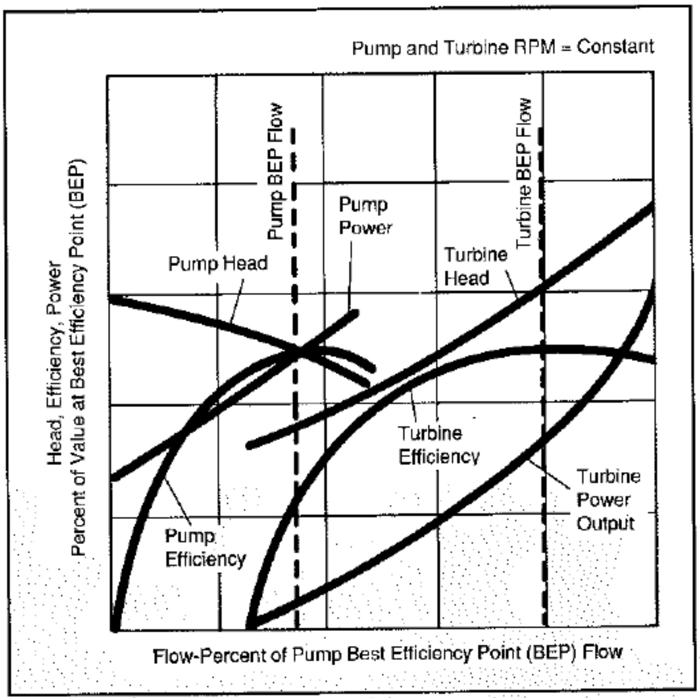

Figure 1: Performance of a pump and a pump-as-turbine (PAT) at identical rotational speeds. (Courtesy *Power & Fluids*, Vol. 10, No. 1)

Figure 3.3: pump and turbine mode comparison for Head curve, power, and efficiency. picture is taken from Paul N Garay, Hydropower review, 1990.

power? as we can see in the figure 3.3 for pump mode, power adsorbed at first increases with flow, until reaching the nominal condition point, where the efficiency is at its maximum. this point is called BEP (Best Efficiency Point). from there on though the efficiency drops, and the pump can't just work much over there. in turbine mode this changes: the overall available power, for a generic hydro-power system, can by expressed with the general expression

$$P = \rho g H Q \tag{3.1}$$

. so, since low discharge means low head (as shown by the qh curve) this implies low power and shaft torque. but higher heads and flow means high power that is what we look for(for sure there are limits imposed by the plant to this but we will be discussed later). but we can not just go on increasing head and flow to get higher power: efficiency also has its maximum somewhere over there, determined by the geometry of the apparatus.

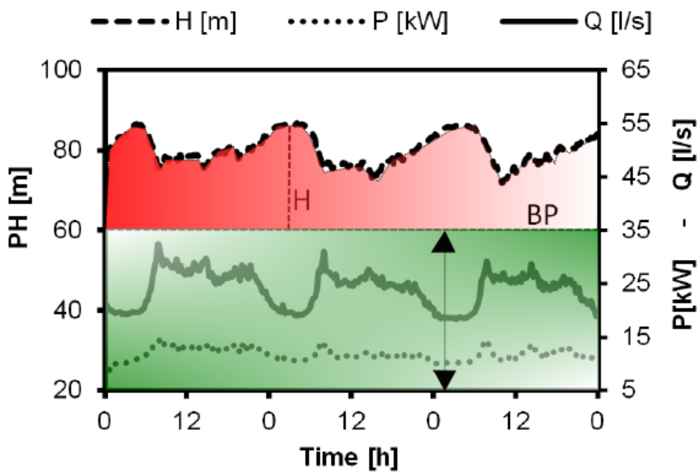

Figure 3.4: a typical WDS daily H variation: is underlined the concept of backpressure: the horizontal line is the H of BP: the area below (green) correspond to the energy lost for matching BP requirements, the area above (red) is the still available energy. (image adapted from [1])

3.2 mathematical model

the curves that we have just seen are the heart of a work on pats, and the first thing in order to make a study on this will be trying not only to understand them, but also to express them in a mathematical way that could permit us to make calculus to get direction on how to move.

head curve for head curve there is not a proper modelling equation that can tell us: ok, that is your turbine? then this is its head curve. or better there are models that tries to do that, few of them and sometimes different from each other[8] (e.g [3], or [2], or [5]). and are usually quite complex: they do have to include a lot of geometry and parameters, usually difficult to measure, and could be that do not fit your turbine since there are lots of different pumps and model changes with the type. so, in the vast majority of the cases, the producer give us directly the q-h curve, as pump. and some models try to calculate the q-h curve in turbine mode starting from this one [2]. among all, we have considered the most the ones proposed by [3, Chapallaz], as reported also by Nygren's [5] experiments and Alatorre [2].
in the specific case of this work i have worked with basically three different theoretical pats, which head curve (on which, as we will see, relies all the model) have been derived from data-sheet of some PATs available on the

market, and then their polynomial fitting curve was used.
remaining in qh graph, another thing we need to know, is the BEP, Best Efficeincy Point, since it varies from the pump mode. also for this one we have to depend on the producer or try to calculate it in a similar manner.

polinomi from the head curve we can derive the others parameters that we need. for calculating power a polynomial model was used, mostly following the guidelines proposed by Alatorre [2], similar to the ones proposed by Chapallaz [3] Hyypiä [14] and Nygren [5].
is a good model, that starts with head calculation from the classical turbomachine theory and, from this, adding various hypothesis, moves to obtain an expression for power, torque and efficiency, function not only of the flow but also of the speed. they proved it experimentally and showed to worked well as explained in their master thesis.

head polynomial curve the head polynomial is derived starting from the Euler equation, and the velocity triangles, with some validated hypothesis such as: geometrical parameters constant; flow angles independent from discharge rate; constant volumetric efficiency and negligible slip in turbine (slip is a little deviation of the output velocity due to a angle simplification, that could reduce a bit the net head). head lost due to friction and shock losses is added to end with a polynomial function of the second power of the flow. this expression correspond to the q-h curve that is sometimes provided by the producer. it can be expressed as:

$$H_{nom} = k_{h1n}Q^2 + k_{h2n}Q + k_{h3n}; \tag{3.2}$$

affinity laws but this equation refers only to the nominal speed and to obtain a more flexible equation we need a model that include also turbine speed, so that we can move to almost any point of the q-h graph when calculating power and torque, and each point feasibility for power generation. to do this affinity laws are used. they are a series of correlations that, starting from a geometrical similitude, derive some comparisons among similar machines with different sizes. they have two main variables, that are speed and the impeller diameter. in this study we will mainly consider this last constant since what we will usually look for is the pediction of the performance of a given pump, with its fixed diameter. looking at how this parameter affects the system could be useful in case of having to design the machine itself, that is not our task. so we will focus mainly on the variable speed effect, since we will be looking at some control cases in which the velocity will be the key control variable. the affinity laws of our interest can be expressed as:

$$\frac{Q}{Qnom} = \frac{N}{Nnom}; \tag{3.3}$$

$$\frac{H}{Hnom} = (\frac{N}{Nnom})^2; \tag{3.4}$$

$$\frac{P}{Pnom} = (\frac{N}{Nnom})^3; \tag{3.5}$$

where obviously the term ”nom” could be whichever, but in our cases we will use it usually this way, starting from the nominal curve, that is what we know more about.
applying this model to the previous head polynomial, we can easily get the following:

$$H = k_{h1}Q^2 + k_{h2}Qn + k_{h3}n^2, \tag{3.6}$$

where the coefficients follow from the 3.2: $k_{h1} = k_{h1n}$;
$k_{h2} = k_{h2n}/n_{nom}$;
$k_{h3} = k_{h3n}/n_{nom}^2$.
this equations allows us to calculate the H-curve for every speed and discharge. we can so obtain the variable speed q-h curve, an example is shown in fig. 3.5.

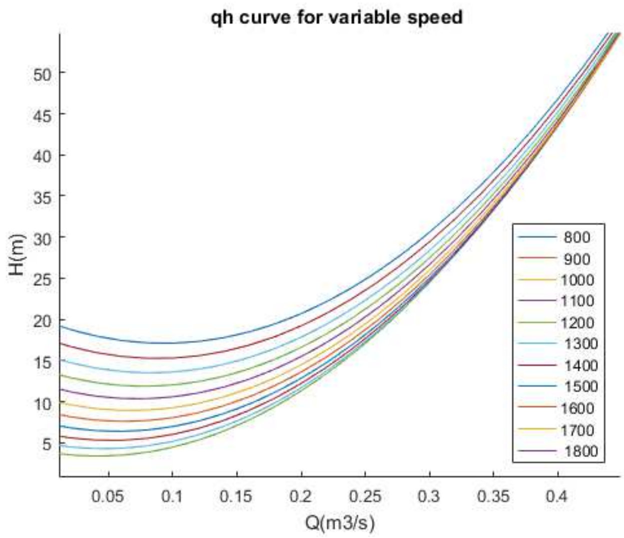

Figure 3.5: polynomial model for head for different speed from 800rpm to 1800rpm. pat’s nominal speed is 1520 rpm, in blue.

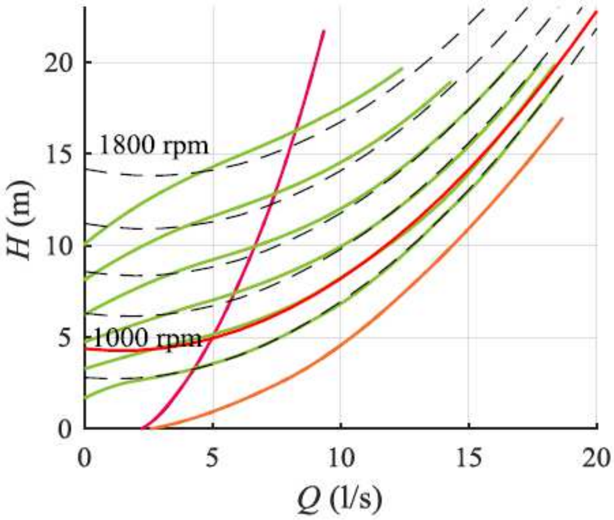

Figure 3.6: comparison between experimental and mathematical head curve for different speed: as can be seen the model works well in the turbine operation area, while for low flow values it stops working. in the fig are presented also runaway and resistance curve, and datas are for the Sultzer A11-50 pat. taken from Nygren's work.

validity the curves we have obtained are parables, as could be predicted from the equation. but in reality the head curve the turbine follow will be slightly different: this one has its validity only in the range of operation of the turbine, that's saying in the range comprised in between the resistance (RC) and the runaway curve (RA), that will later be introduced and explained, but that basically represent two generation limit condition for every machine: respectively no torque (T=0) and of no speed (n=0) working situations. in fig 3.6 we can see the difference (for different speed) between a theoretical and an experimental curve: the model works well for the flow values of the turbine operation range, while it differs reducing the discharge: the polynomial curve would imply a re-increase of the head value, while it drops to zero.

we have so to remember that the validity of our model is limited to this area, as shown in fig.3.7

power, torque and efficiency

power in the theoretical model, power final equation comes from taking the various power losses occurring in the process out of the overall power

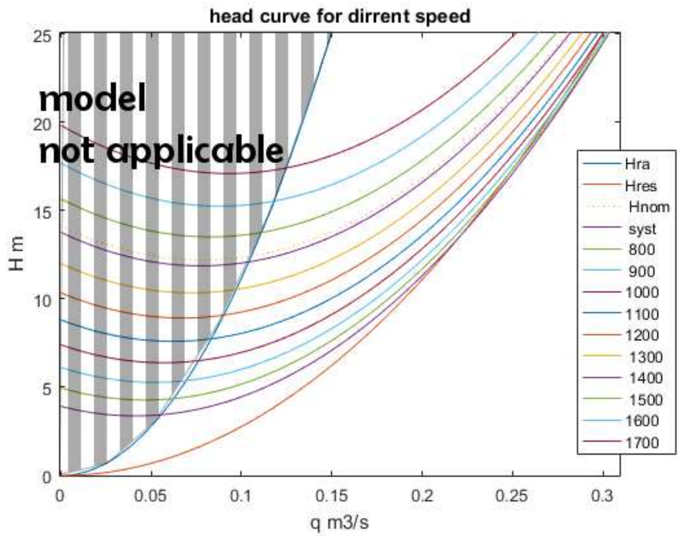

Figure 3.7: head model is not valid over the runaway curve

expression 3.1, solved for flow (or of head if needed) inserting for H its polynomial expression 3.6; losses included in the calculus are shown in the figure 3.8. we obtain:

$$P_t = k_{p1}nQ^2 + k_{p2}n^2Q + k_{p3}n^3; \tag{3.7}$$

coefficients for this expression have to be evaluated. the best thing is do this experimentally. in my case, not having a real pat at the moment, for this purpose i have used the polynomial model proposed by Derakhshan and Nourbakhsh [4] to compute nominal power from nominal head curve. is to say that this model has not been tested widely and was the result of fitting some experimental results obtained with a few pumps. that is for sure a limitation to the validity of the numerical results obtained, but not to the theoretical model proposed and to the method itself. it can be considered not that relevant since no calculation are reported, but a control method proposal.

$$\frac{P_t}{P_{tnom}} = -0.3092(\frac{Q}{Q_{nom}})^3 + 2.1472(\frac{Q}{Q_{nom}})^2 - 0.8865(\frac{Q}{Q_{nom}}) + 0.0452; \tag{3.8}$$

and then dividing for the nominal speed at the various power.

power for different speeds is plotted in fig. 3.9. as before, the validity of these curves has to be considered only in the working area of the turbine, while the mathematical curves covers all the plane.

these curves are really interesting to us: they show that varying velocity

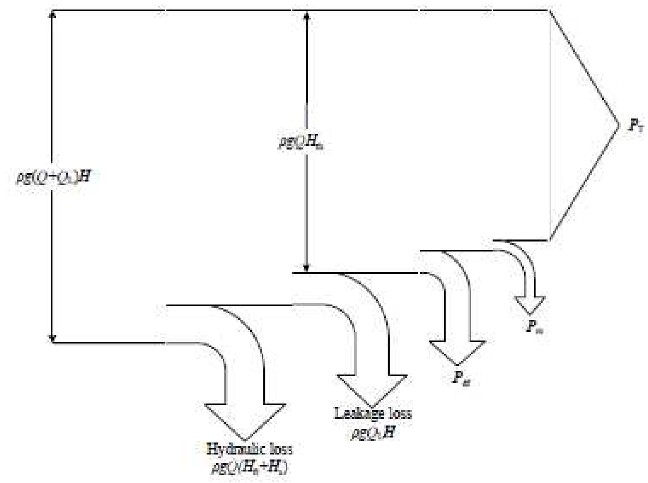

Figure 3.8: power model derivation and how we get the turbine sharft power expression: sankey diagram, from Nygren (2016)

could help maximizing power: in fact for different flow conditions we can see how the speed giving us the higher power production varies, and varies exactly in the flow range of interest as working area for our pump. here is where we will go to work and to control our turbine to rise the efficiency of the system through electric regulation. can be noted that for low discharges we maximize power decreasing shaft speed and viceversa.

torque expression for torque can be determined dividing the power model 3.7 for the speed, and coefficients come directly as $ktn = k_{pn}/(\frac{2\pi}{60})$; torque polyn. results:

$$T = k_{t1}Q^2 + k_{t2}Qn + k_{t3}n^2; \tag{3.9}$$

. about the torque can be interesting spending a pair of lines more since it can not be so clear in this case of wich torque we are talking about. the water pushing the pump blade arrives with an energy, and will exchange part of this energy depending not only on the geometry of the machine, but also on the impellers speed, and from the shaft resistance it goes through. if for example the shaft is not connected to any electrical machine or brake of any type, water will force the machine to go to work to a definite speed, called runaway speed, that is gien from the equilibrium within the forces exchange between water and blade. so regulating the electro-magnetic torque inside the generator means forcing a determined working point where as maximum

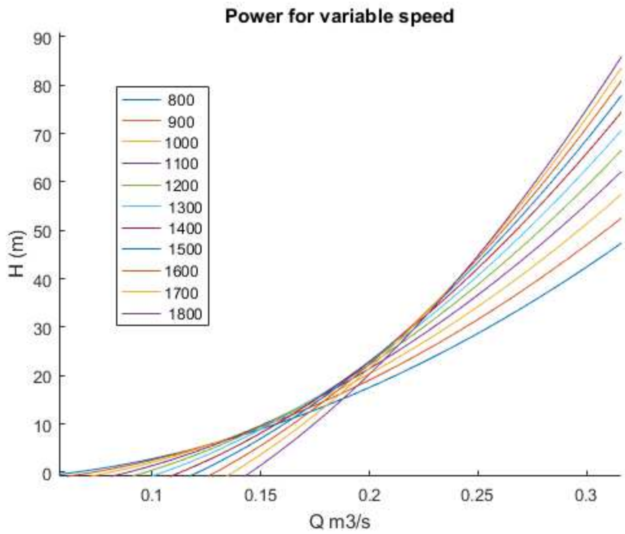

Figure 3.9: power for variable speed: power for nominal speed is marked with dotted line

the previously calculated power can be transferred from the fluid to the shaft (and then, with its efficiency, from this to the grid by the generator). torque exchanged between turbine and the electrical machine will so be always the same, with opposite sign, assuming the shaft to be rigid.
to help us understanding where to go to work it will help us having a torque curve function of speed: for the turbine, this curve should be a straight line according to Alatorre's [2] complex model. from our model (as shown in fig. 3.10) the result is a line a little more curved, but it is acceptable, and phisically reasonable: for decrease speed we need more torque with the same water flow.

efficiency efficiency for a turbine can be expressed as the turbine power 3.7 divided by for the general power 3.1.

$$\eta = \frac{P_t}{\rho g Q H} \tag{3.10}$$

, substituting H 3.6 we get:

$$\eta = \frac{1}{\rho g}\left(\frac{k_{p1} n Q^2 + k_{p2} n^2 Q + k_{p3} n^3}{k_{h1} Q^2 + k_{h2} Q n + k_{h3} n^2}\right); \tag{3.11}$$

we can now calculate efficiency (η) for each different speed with affinity laws and the result is plotted in fig. 3.11.

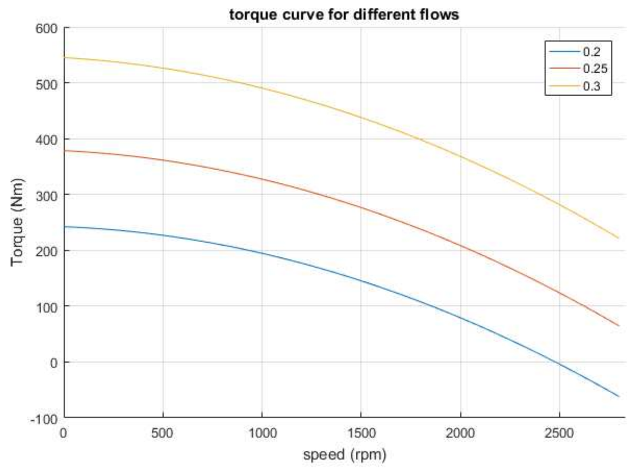

Figure 3.10: torque characteristic for different flows (in m3/s)

limits of the polynomial model pt1: efficiency as can be seen the efficiency curve basically translates, and for each speed we get the BEP (best efficiency point) for a different flow. that sound. there is though something to say about this model. in fact the efficiency curve shape is always the same for every different velocity, and this does not correspond to reality. it has been demonstrated that as far as we go from the BEP of nominal speed, we always get worst η. this is a strong limitation to the affinity laws (AL) model, and a proposal was made by Fecarotta [40] to adjust these problem, but resulting in a much more complex model. we report in fig. 3.12 the interesting results he got: some experimental pat data are plotted with respect to the actual speed and nominal speed ratio.

as this ratio increases or decreases, we get evidently lower η. the efficiencies obtained with this model are plotted on fig.3.13

and if for what regards power his model results more accurate, at the same time this study demonstrate the validity of the AL model for head and flow. in this work we will go on with the AL model, taking thus in account this sickness.

limits part. 2: coefficients proportionality staying on the theme of the limits of the polynomial model used, is to underline the influence of the various polynomial coefficients. as already said, we try to work with the affinity model but starting from some curves, that are usually derived experimentally. and the model dependence from Q, for example has been derived making hypothesis, that in general work well. but some paramenter vary their influence on the model according to speed or to size or to some

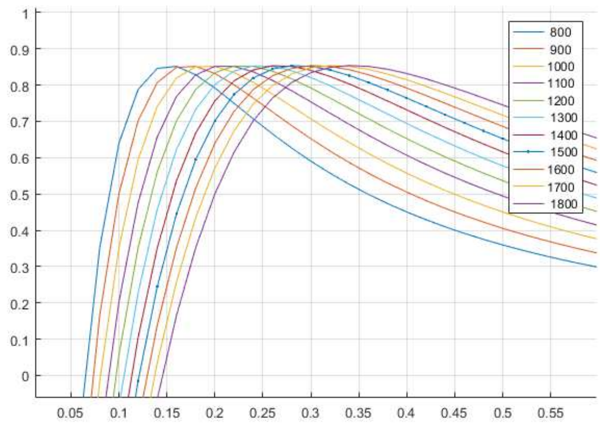

Figure 3.11: efficiencies for variable speed with Affinity Laws classic model

other variables, so in the end, the model, as the best model of whatever, will have some limitations when trying to represent all a panel of different situations. among this, referring to the coeffincient of the polynomial curve there is an interesting study on the trend of what we called kh1, kh2 and kh3, respectively a,b and c in fig. **??** . experimental measurements have been conducted for a same pat at different speed, measuring H curve, in order to study the effective relation between the Q and H. the results is that the hypothesis we made with the affinity of having:

1. $kh1 \propto Q^2$;
2. $kh2 \propto Q * n$;
3. $kh3 \propto n^2$;

is not exact. but once again it was not supposed to be, and moreover we have here an assurance regarding our tendency: the main term of the polynomial expression of each is in fact the one corresponding to our hypothesis.

method all of that stated we have now an idea of how the proposed model works, and of which are its main limits. in the following work i have basically followed the proposed model, starting by some head curves, already in turbine mode, of an hypothetical PAT, which values were taken from experimental data, not yet published, that i got thanks to a courtesy of Novara. the experimental data i got have been modified to have a turbine to be adapted to the various situation required by the study, and is always about having

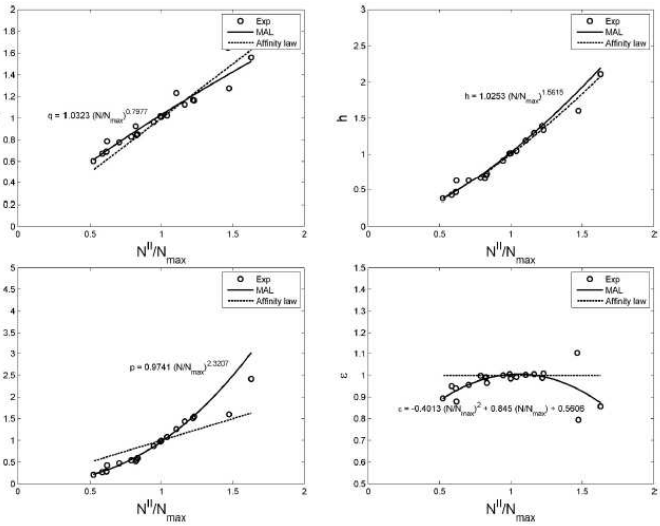

Figure 3.12: affinity law (AL) model compared with the ModifiedAff.Law model proposed, in front of some experimental PAT test measurements. we can see how already in power model AL is not that precise, and when coming to efficiencies it does not take in account the variable speed effect.

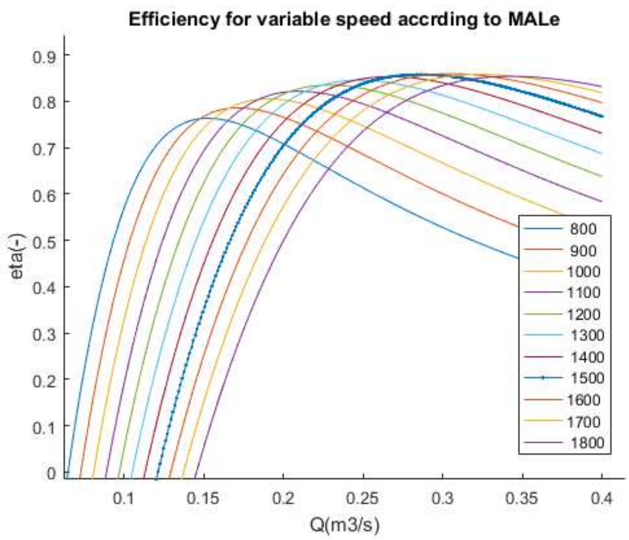

Figure 3.13: efficiencies with MAL model: they vary according to speed and nominal speed ratio. taken from [40]

a turbine to use as an example to explain a general model proposal. with this curves i have obtained the coefficients for the whole model, calculating the power, as said, with an empirical polynomial, that is maybe the biggest sickness of the whole model.

Chapter 4

Typical pat installation

we are slowly deepening in the world of pats. what we know need to know in order to start to design a control, is the typical scheme of installation: which are the main actor, and what they are supposed to do? which of them are mandatory and which of them we can try to take out in order to modify system characteristics according with the specification we are trying to match?

system curve and working point before going in detail of the single elements composing the typical installation we do have to say something about the system itself.
the working point in q-h plan will be determined, in fact, from the intersection of two curves: the head curve of the turbine, that we have seen before, and another curve, that will be determined by the system. what will affect this curve? geometry for sure, and then the operation instant conditions. geometry because as we are talking about hydropower and the head parameter depends on pressure. and hydrostatical pressure depends on the height of the water column over the physical point in which we are working, it is saying the difference in height between the turbine and the free level of water. this works in case we work with a basin or a static reservoir. but pressure in the key factor also in dynamical situation, e.g a WDS, where inlet pressure and flow could vary during the day, moving in this way the system curve. we will so have to follow this variations and study how to react to get the bigger advantage from every situation.
but how is it a typical system curve? there are two main cases: the hydrostatic-only pressure, e.g. the case for examples of water tower at atmospheric pressure or of water basins such as the exit of a wastewater treatment plant. in these cases the head corresponds more or less with the hydrostatic gap minus the friction losses in penstocks. system head curve will so be a line crossing

the head axe in the value of net head at the basin free level and decreasing more or less (friction factor depends upon several factors as geometry, flow regimen, speed etc) with square power of the flow. in fig 4.1are plotted some system curve varying the ΔH and the friction factor.

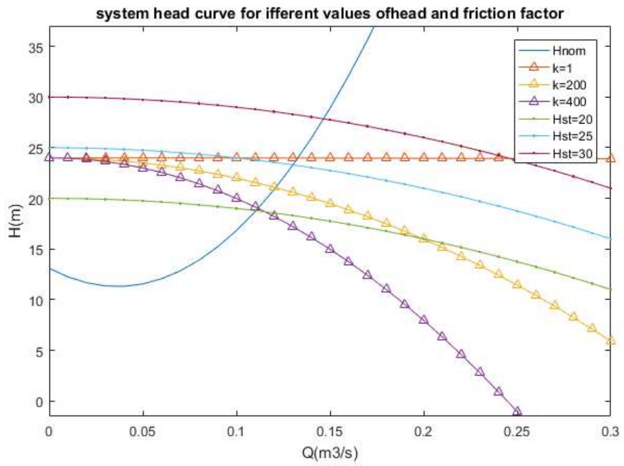

Figure 4.1: how friction factor or inlet-outlet head difference affects system curve: 3 different ff with the same dH=24m and 3 different H with ff=100 are plotted

but friction is not the only parameter affecting system curve: instead we are in the very particular situation of a basin always at the same height, we will have variations also for the static head: as the water level rise in the storage tank, the head will rise, for example. or in case of variable inlet flow conditions, flow and head will vary during the day. an example of a daily evolution of this two parameters is presented in fig4.2 .

and not only the inlet flow conditions changes: it could be that also the outlet constraints are fixed by the application and we do have to match some criteria on this. with this purpose, f considering the outward constraints of the plant, we introduce the concept of backpressure (BP): it is the pressure head we must provide at the exit of our plant, and it is fixed from external requirements. BP affects our system curve shifting the horizontal axe upward: we will have to work no more whit all the inlet head, but with the head difference.

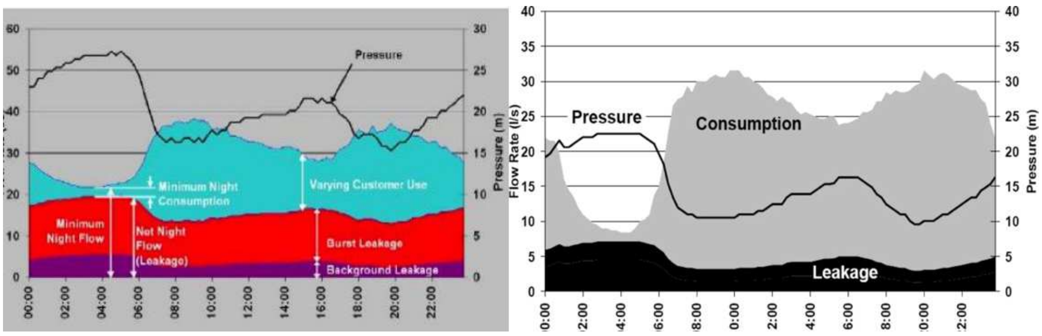

Figure 4.2: two examples of daily evolution of pressure and flow in a WDS. taken respectively from altratecnica.files.com/perdite-pressione.jpg and researchgate.com

4.1 typical system

the most classic installation scheme of a pat is the following: as we can see we have different elements that will be discussed one by one following. briefly they are:

1. the pat itself;
2. the electric generator;
3. the power converter;
4. the series valve;
5. the bypass valve;
6. the electronic controller;
7. flow and/or pressure meter(s);

4.1.1 valvole

valves are the basic element of whatever traditional system that wants to match the objective of somehow regulating a flow. they are one of the most common hydraulic actuator and they can be opened or closed in order to let pass all the flow, just a part of it, or to stop the discharge at all. there is a big variety of valves on the market, and it changes the way they are driven (e.g are there electric, mechanic, pneumatic), their mechanical construction and the flow they can accept and regulate. there is also a differentiation in

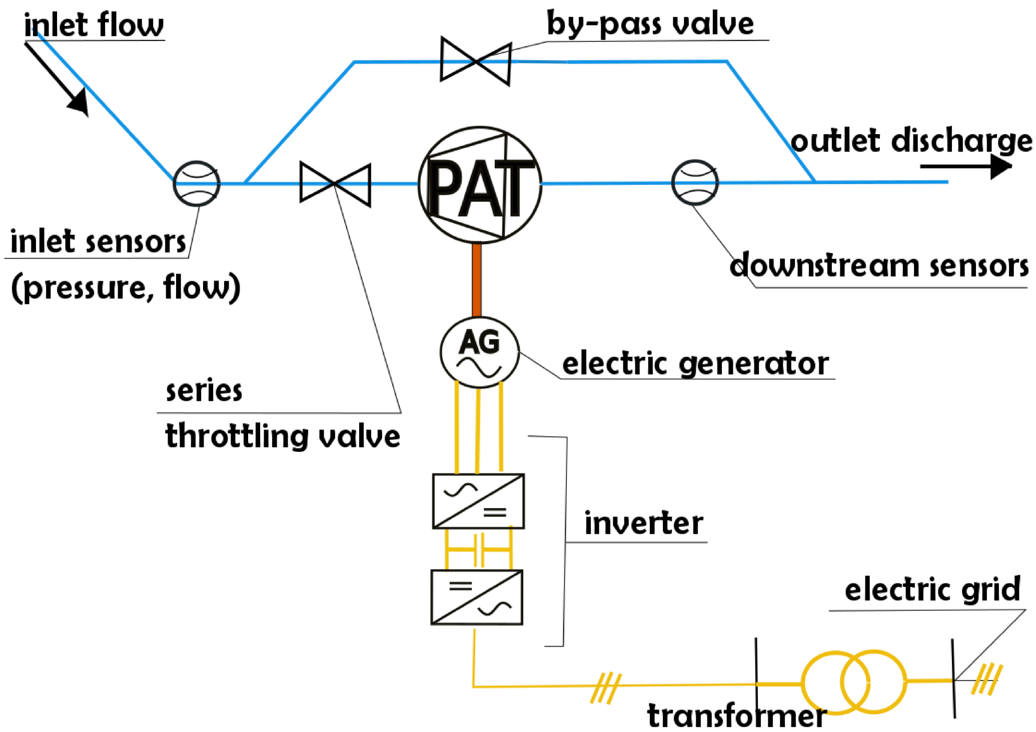

Figure 4.3: typical pat installation scheme. yellow line represents electricity conductors, blue ones water. in brown mechanical shaft.

how fast they open and of which percent of fluid passes according with the opening percent of the valve, but we actually are not interested in this, and we will assume linear valves, in which opening half means letting pass half of the inner flow. for sure is then something to care about at the moment of designing a specific plant.
in terms of controlling valves are fundamentals since they permits us to actuate the simpler but maybe more interesting control: the hydraulic regulation that will later be discussed better. to give an idea it is sufficient to look at how they affect the curves we have already found. they acts modifying system curve: since the working point is the result of the intersection of the turbine head curve with the system's one, being able to move this permits us to control the working point. in this way we can, without any electric regulation, decide the flow discharge we want. has can be seen in fig. 4.4 we can theoretically get all the flows comprised in between the flow imposed from the cross point within system and turbine curve, to zero.

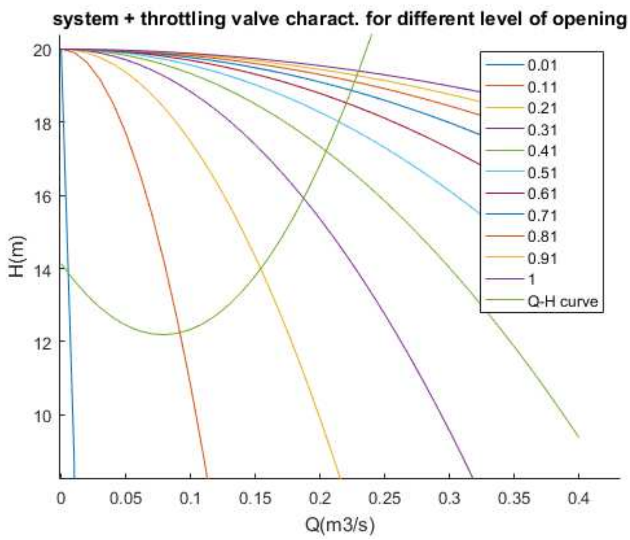

Figure 4.4: how a throttling valve affects system head curve: assuming 0 as full opened (we obtain system curve) and 1 as fully closed (no flow condition). turbine head curve is also plotted.

mathematics of valve the discharge that passes through a valve depend basically on two main variables, the head gap over the valve itself and the relative opening, and some parameters depending from the valve construction (materials, geometry, frictions ect.). a general law to describe this is the following[18]:

$$Q = K_{vmax} \cdot x \cdot \sqrt{\frac{\Delta p}{\rho}}; \tag{4.1}$$

where Δp is the pressure difference and ρ is the fluid specific density. the term $K_{vmax} \cdot x$ is usually called k_v (in europe Cv, slightly different), and is a parameter function of the valve type, and express basically the correlation between the opening and the fraction of the maximum discharge that will pass. there are different expression of this k_v[14], but we assume the hypothesis of working with linear valves, so that we can express directly in the way shown. also about the variable "x", the relative opening some literature [26] reports different expressions including the fact that for some valve the flow start and stop limits do not correspond to the "end course" position of the valve actuator, but here, once again, we assume it to be the simple opening. in a real case, thus, could be important remembering of such hypothesis in case of problems in regulation.

series and bypass valves in order to control the flux it is common to place at least two main valves: one in series with the pat, and one controlling a parallel branch, called bypass valve.
the series valve, is a throttling valve, and its aim is that of dissipating excessive pressure head: it is needed in order to regulate the inlet flow, moving downward the system curve, actuating the regulation we have just seen. doing this means in the valve has to fall the difference of head between the inlet fluid an the water arriving at pat's impeller. without this element the system curve is fixed and to regulate we will have to work only on the turbine curve. bypass valve instead has the role of regulating the discharge passing through a pipe parallel to the pat, so it regulates how much of the inner flow will not pass through the turbine. when this could be helpful? for sure in case we have a bigger flow than the maximum allowed for the turbine, but also other cases could happen, in which we need less power than the available, or we have to match other requirements.

4.1.2 asynchronous machine

first of all why asynchronous? it is not a mandatory choice, and the possibility to use different type of electrical machines (e.g brushless synch.) could be interesting to study. but in this work we consider only induction motor as a choice, for different reasons. the first and maybe most important is its availability and reliability. induction motor is far the most common and cheap electric motor on the market [22] is really well known, and was extensively studied [36]; is a really flexible machine (e.g. a synchronous not controlled could not work if not at its synch speed); it can be controlled in different way and a suitable controller can be easily found. all the stated aspects match well with the idea of a pat installation: something that should be cheap and reliable.

induction motor the IM is composed by a stator and a rotor, coupled by a purely magnetic connection (no brushes are needed).the stator have to be supplied by an external power source in order to generate a rotating electromagnetic field that creates the conditions for corrent to be induced in the rotor, that is usually short-circuited in a squirrel cage. this induced currents creates another electromagnetic field that rotates at a speed really similar, but slightly different from the stator one. this difference (that, normalised to stator speed is called slip) is fundamental for the machine functionality and makes the motor produce torque. it works at a synchronous speed fixed by the supply frequency by the law $n = 60 * f/p$ where f is frequency and p are the pole pairs [23], and the effective rotor speed will be a little slower according to the slip: $n = \frac{60*f}{p}(1-s)$. it can run in a quite large range of speed, and a limit could be set in$+-30\%$ of nominal speed.[22] and is usually due to the thermal limits of windings.

IM as a generator what happens if an IM is driven at a speed higher than the synchronous one? it is the case of an external torque, higher than that produced by our machine, is applied to the shaft. currents will be generated in our motor's stator windings, and it will start generate electricity. in other world, when slip goes negative, our machine enters the generating area.

so an IM is itself a generator: no changes are needed. there are though some considerations to be done before using the machine to produce electricity.

as happens for pats, also for IMs it is sometimes not that easy to have the torque or power characteristic for the drive, that is commonly designed for its motor mode. but the use of asynch. generators is becoming everyday more common, thanks also to the diffusion of wind generation, that uses a lot this kind of machine, mostly for the same reasons explained here above for our system, so that is not that difficult as for pat to get it. the main differences in the behaviour in generator mode have been studied for example recently by Hadziselimovic [21] that in a really interesting paper shows

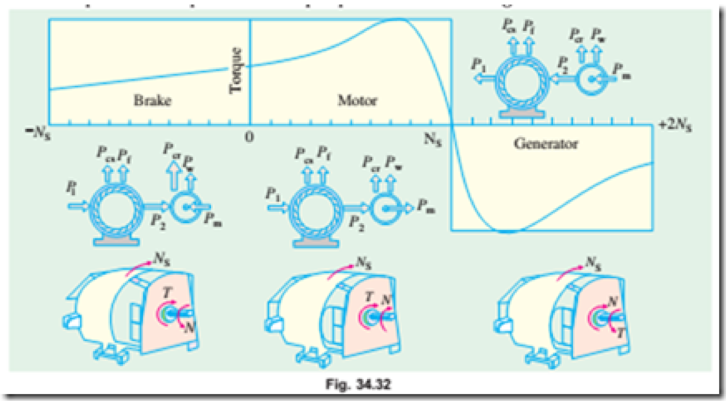

Figure 4.5: different region of operation of an IM. from http://machineryequipmentonline.com/electric-equipment/induction-motorcomplete-torquespeed-curve-of-a-three-phase-machine/

how torque characteristic differs in motor and generator mode (as showed in fig 4.6, similar to [32] and to [23]) and how this affects the performance. breakdown torque (bdt) results to be higher, up to 4 times the bdt in motor mode. this means a potential much wider operating area in generator mode. also efficiency rises and thermal losses are reduced for the nominal power.

torque characteristics and sign conventions we said for the pat sign convention where fixed by the pump chart. in the case of the electrical machine we can either consider we are in the second or fourth quadrant: in both cases we have positive Power produced. the two options are shown grossly in fig. 4.7. since we are generating is maybe more useful working in fourth quadrant, with negative speed and positive torque.

pro and cons of IM talking in terms of advantages we have all what already stated on market having plenty of them but not only. something that could help the design of a pat plant is the fact that some producers provide a pump directly with its motor: that means that the mechanical junctions are already made, that implies easier design and reduction in cost[26].
another good one is the behaviour in case of fault: since it has to be supplied in case of electrical down of the grid it would not supply the fault. on the other hand this is at the same time a disadvantage since it means it can not work in an isolated grid (or at least it can but a starting system has to be designed to provide electricity in the first instant and then some power produced has to be spent to create the EMF, and this could affect the power factor, since we are talking of reactive power).

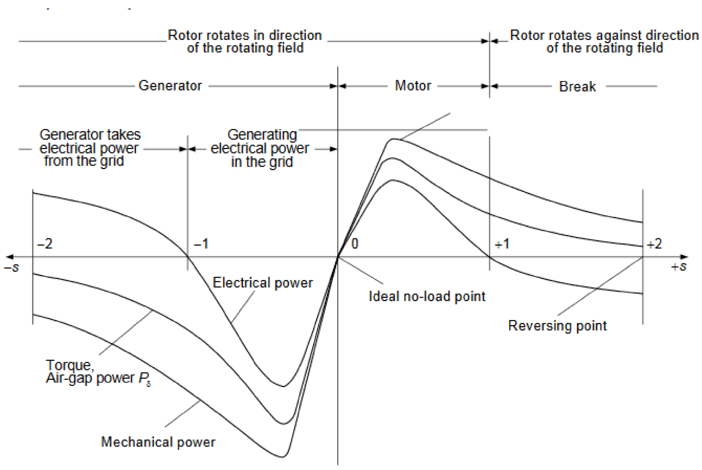

Figure 4.6: torque-power characteristic comparison for generator and motor mode (Hadziselimovic 2013)

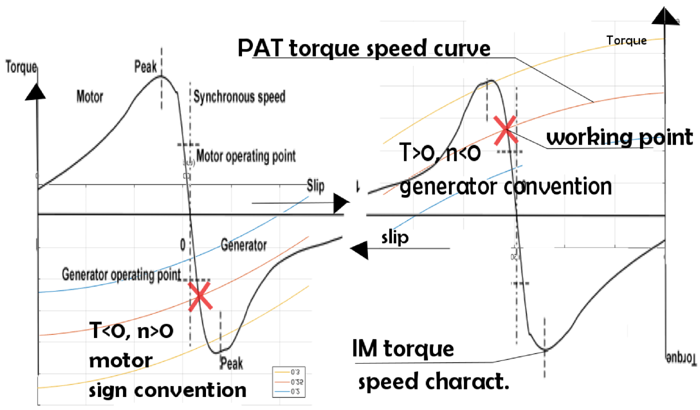

Figure 4.7: torque speed curves for a pat (different curves are plotted for different values of flow, 0.2, 0.25 and 0.3 m3/s) and a generic IM: the same situation is depicted with the two different sign convention: of the motor, with positive torque produced, and as generator, with torque positive when received.the IM curve is adapted from http://masters.donntu.org/2006/eltf/revenko/library/indexe10.htm

robustness of the rotor also helps its reliability: synchronous machines (with the exception of brushless ones) have to supply electricity to the rotor. this is a negative thing in case of mechanical fault: an induction generator can go to work at runaway condition, while a synch. one could have problems with brushes at high velocities[6]. another thing to say is that usually efficiencies for synchronous machines, when designed as generators are slightly higher than for IM, but especially with the newest we are talking of high values also for this ones. to give an idea the medium efficiency for an IM is between 70 and 90%. [26]

advantages	**drawbacks**
Small size	have to be excited
Robust rotor (brushless)	not self starting (no standy power)
Simple in design	
Light and compact	
Low maintenance	
Low cost	
no fault supply	
high availability	
flexible	

controlling an IM also on this topic there is plenty of literature and different ways of controlling an IM are present. the basic idea of any induction drive is controlling speed somehow through frequency, since this two are directly proportional. the maybe [22] most common control drive for IM is scalar control, or V/f, and consists of increasing voltage together with frequency, in order to keep this ratio (V/f) constant. its quite a simple control and was and is widely used. now is usually preferred the most precise vector control, that usually has a torque loop inside the speed one and proved to give better results, even if it requires a high computational power. vector control can be performed both in a sensor way, measuring speed through a sensor (usually an optical encoder), or sensorless, estimating velocity from the current measure. the first of the two is way more precise but this means also more expensive, while the second one has proven to give really good results with a good compromise in cost/performance.[36], [20].
in this work we will consider the control loop of the drive to be independent and work on himself to reach the speed reference we will pass him trough our micro that will be independent. so we consider the electric drive as a block, as a box including inside the machine, but also the power electronics, the sensors needed to close the loops, and the micro performing the control.

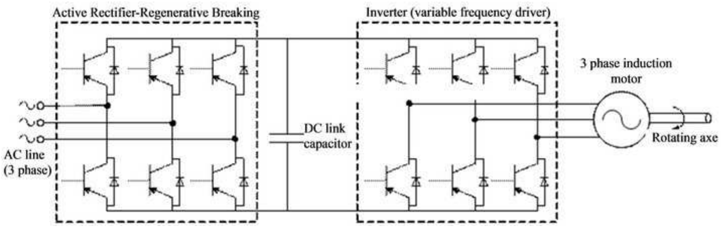

Figure 4.8: typical regenerative converter (Energy and Power Engineering Vol.5 No.3(2013),)

inverter the inverter is the key part of a totally controlled pat system: while it is not necessary if we do not intend to operate the ER, it is who actually make ER possible. what an inverter is? technically it is a power electronic (PE) apparatus that converts a DC signal to a as sinusoidal as possible one. but it is really common that is called inverter not only this part, but all the equipment needed to transform a power signal in another one with different characteristics. in our case we will need a PE equipment to convert the power we produce with our IM, but not only: we need also to generate the synchronous rotating magnetic field that needs the asynchronous generator to produce power. but this is not the only converter we need: if we intend to produce power to be fed to the electric grid, we need to produce a power signal with determined characteristics: it will have to match a frequency level, a tension value and a power factor limit. this means adding part to the installation, that are costs and inefficiencies, and have to be designed. the first part that we have to add is the grid-side converter. then we could probably need a filter or an apparatus cto compensate reactive power eventually produced in some operating conditions, and the transformer, depending on the generator we have.

we really need the grid-side unit? we will need it almost always, except in really rare cases in which we could be interested in using the power as DC: could this be the case of a plant constructed in order to supply a specific equipment (e.g. an light system) that does not need AC, or the situation of planning a little grid that operates in DC for some reasons. a possibility to lower this element cost is that of using a common dc link for different machines: each of them would have its converter to link them with the dc bus, and one bigger converter will comunicate with the grid. this option could suit for some cases of parallel operation for example; or for example in the case of energy storage from photovoltaic, that of using the solar same DC link of the solar panel inverter and use this one if we need to supply electricity to

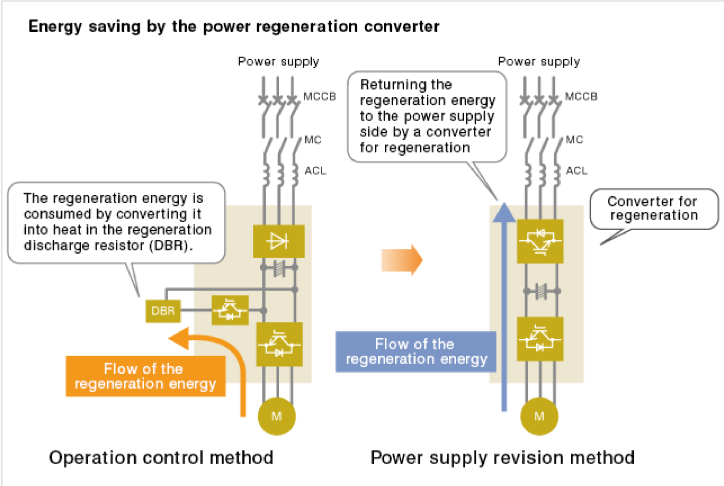

Figure 4.9: difference between a frequency converter for IM supply and a regenerative converter. http://www.meidensha.com/products/industry/prod 02/prod 02 01/prod 02 01 03/index.html

the grid for some reasons.
in general though we will imagine that the two are present together, since is the most common situation, and that are connected through the DC bus, that will be provided of a capacitor stabilizer and an eventual brake resistor. and we will call all this stuff inverter for ease, since we will not look inside the PE.

regenerative units ok, as stated we will need an inverter that presents a conversion unit. is this easy to find on the market? it is, but not as much as it could seem at principle. for the reason of calling inverter whatever PE equipment in fact, we do have to care that the converter we are buying is provided of the inverter grid side: since the majority of AC-AC frequency regulator power converter on the market are intended to feed some IM used in motor mode, they usually present a diode bridge at grid side, that will not allow power to flow back (without inverting the dc-link polarity). we will then need a double bridge or, to have a better harmonic result a controlled converter on grid side also, as shown schematically in fig.4.9.

inverter control and communication we have now seen the "power side" of our electronic converter. but the big functionality of a electric drive is given from the CPU operating it. to get a flexible system and take profit of the flexibility of transistor technology, that relies on their easy operability we have to add to the system something telling the inverter when and how commutate its IGBT (isolated gate bipolar transistor, the most common power transistor used in inverters nowadays). this is done by the internal control of the inverter, another element that we will include in the general term inverter. it usually comes with the inverter and is a micro that allows us (users of the drive) to set different modes of operation, including the possibility to set manually some parameters (as speed reference), or setting it via external equipment (see later: parag. external supervion for more on this) in different manners (databuses/digital or analog inputs).

from frequency regulation to Direct Torque Control (DTC) this micro could perform different types of controls, more or less complicated, and more or less demanding in terms of computational power. without entering the big world of induction drive control, we can just say that the idea is something like:

1. taking a reference (e.g. speed),
2. compare it to a somehow calculated/measured value of the actual situation of the motor,
3. generating a commutation logic string for the inverter that will depend on this error,
4. repeat until the error disappear;

inside this really general scheme there are a lots of different theories and models, with their costs (cpu, sensors needed) and their precision, as anticipated in motor section. among all the model that is quite establishing as one of the best set is the Direct Torque Control, that is schematically showned in fig.4.10 . the more external loop is that of speed that receives the reference as an outside input.

inverter role in pat control how the inverter can affect our system control? we were talking about electric regulation, but what it means operating our rotor at different speeds?
to answer this question we can imagine of having a constant inlet flux, and no ER nor HR regulation, but the pat connected to the grid. in this situation the we would go to work to the point fixed by the head curve of the turbine. and what about speed? it would be imposed by the grid frequency and be the synchronous speed, plus (since we are generating) the slip. if we now think

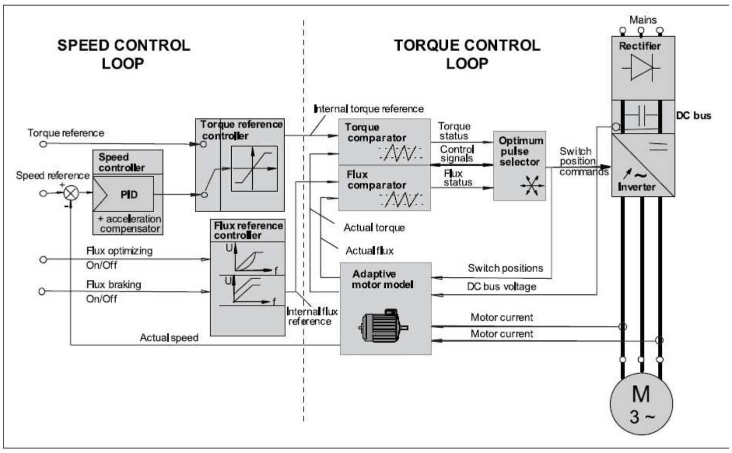

Figure 4.10: DTC illustrating scheme:current measurment is used to perform the motor model computation, speed error influence torque signal to create, throug hthe comparators tha gate logic for the inverter. (ABB tech. guide)

of adding the ER, and change the speed of the rotor: what will happen? flow will decrease a bit, and consequently the pressure head will rise if the inlet flux has not changed. but that on the qh graph means moving upward, as in fig. 4.11

and what about the opposite situation, if we would lower the speed? it would happen exactly the opposite, with flow increasing and pressure head lowering. this is ER: regulating the flow through the speed reference.
in terms of head curves we are just moving the head curve up and down: this allows us to decide where to move the working point (the cross between turbine an system line).

SCADA control systems and role of our cpu in a Pat system, we have said usually the cost should be minimized as max as possible. and since to have ER possibility means we are already facing the cost of the inverter itself, we should try to lower the cost of the external controller. the idea of this work was to develop a simple algorithm that could be charged in a commercial microprocessor: a really cheap equipment that can easily be configured and interfaced through analog and digital input/outputs. this could work on its own without problem in case of a stand-alone installation, being a good compromise between performance and cost; at the same time it could be connected to a wider control system, such as the SCADA system control for a WDS. in this case the same equipment could work perfectly, fitting in hierarchic solution, such as a master slave configuration, with the slave being our micro controlling the single pat, and the central CPu/PLC

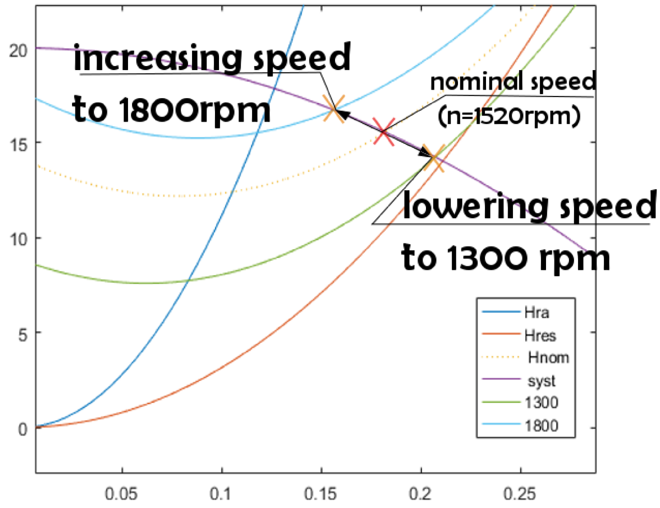

Figure 4.11: electric regulation for 1300rpm and 1800 rpm, starting from nominal speed of 1520 rpm.

system communicating it how to control the flow fluxes of the water grid. another solution, even cheaper could be that of trying to use directly the inverter control cpu to perform the control. some inverter offer the possibility to charge a programme, many more to insert some points of the Maximum Power Point curve, that will be obtained and explained later, in 6.1.1.

sensoring the system for what regards knowing the available head we can have three cases:

1. it is constant and known (case of a constant level basin);
2. it is unknown but we know the system curve (H(Q)) and have the flow measurement;
3. we have a pressure meter;

regarding the sensors there is really a lot of literature of electronic instrumentation, and, more, there are really lots of them: many different physics principles can be used to measure flows and pressures. and of every kind of sensor there is such a variety in dimension and precision, that make vary the cost: we have sensors that cost few euros and sensors for thousands. we are not entering this world, since too much variability is there and usually the main case is we already have some sensor in the plant we have to construct, placed previously to manage and control the system (is the case of WDS and of the majority of already existing plants working with pressure differences). so the idea is always go for the economic one and take profit of all the already available informations. in the model construction we will suppose we know both of them and that the processing and conditioning of this signal is done for us by the sensor electronics.

Chapter 5

Controlling pat

after giving a look to what a pat is and how it is usually mounted, we can finally go to the point: how can we control it the best way? how can we act on the system components to get the best performance and match the two main objectives, of having the plants constraints satisfied and the maximum power production? what we want our pat will do in each working situation it could happen?

5.1 hardware

first of all, in order to design a control strategy, we have to give a look to all the instruments we have enumerated until now.
starting from physical world it is interesting to state once again the players we are facing with: what can we control? this question is fundamental to identify the inputs and outputs of our system. a scheme of the system with the controller is presented in fig.

5.1.1 inputs

for what regards the input there is not that much to say, it depends on what sensor are mounted or we plan to buy for our plant. the more the info, if useful, the more precise the control will be. usually we will have a flow and a pressure measurement and, if needed we can get some datas from the inverter control, such as power output, that could be useful in case we operate to match a specific external power request. within this the most important will be for sure the info on the inlet (and outlet) flow but, clearly, some controls will not be possibles without some instant informations.

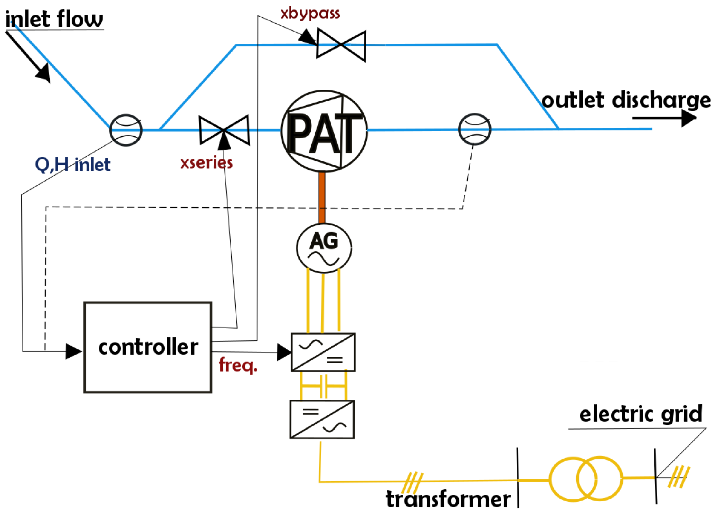

Figure 5.1: typical system with its control: are identified the input , schematically represented as only one sensor, and the outputs: the two valves an the inverter.

for what regards the nature of this signals once again (as explained a bit deeply in the outputs paragraph) for this theoretical study we intend the sensor to be provided with their signal conditioner, and to receive a signal we are able to understand. for sure in real applications the signal arriving from the sensor will probably have to be conditioned a bit, both for what regards the electrical part (tens) and the codification. we can here, for simplicity imagine we got analog signals.

5.1.2 outputs

in our common systems the possible actuators are three: the two valves and the inverter, so some output signals going to drive these elements are going to be the exits of our control system. they are what our control program will have to compute. and how will they be made? it depends on the specific machine we will be working with. here we could get into the big theme of data transmission and of signal conditioning. it is not the objective of this present study, so the possibilities of communication of "high" level, such as data buses and eventual interconnection with supervisor control systems (e.g. SCADA) or other controllers is not considered (but in the idea of planning a distributed intelligent water grid should be done). we will so consider that our micro will communicate directly with the actuators, through analogic signals that some circuitry internal to the actuator element will be able to understand.

speed reference given the possibility, for the majority of the industrial inverters in the market, to receive an external command through an analog port, we will design a program providing such a signal, considering that to convert it to some digital standard would be easily done via software or hardware by adding a A/D converter. this analog input will be set, through the inverter HMI control, as the speed reference for the rotor: the torque control will so adjust the frequency internal reference in order to achieve this one.

valves signal control for what regards the valves, we can consider have 2 different situation:

1. the valve cannot be controlled: we just have to provide a digital signal of open/close; or

2. the valve can be regulated and we have to specify how much we want to close.
   we are usually in this second situation, that is for sure more interesting for controlling, but we will consider also the first since it could occur that maybe one of the two (bypass one) could be of this second kind (for sure cheaper but almost no control possibile).

to drive correctly the valves we should know exactly how they are built inside, if they are driven pneumatically or electro-mechanically, and the circuit specifications: hydraulic circuit for pneum. and the servo-motor datas for electr. these will not be considered in the theoretical work.

loop frequency and priorities order another consideration to say, before entering math and software world, regards the timing of the system: our control will operate in front of a flow change, that is imagined to be a quite slow and low frequency event, talking in control terms. is important to remind this to underline that there should not be interference within the control reference elaborated by our controller and inverter's one. this last in fact will work with the torque and the current loop that have both timing much more faster that flow change. this thing almost garantize us that at the time of a flow change, the inverter control will have for sure terminated its task and will be working at regimen, that means will be ready to act the next task without problems.

5.2 exploring QH plane

after this panoramic view on the control system HW, we can pass to the heart of all: how we want to control our machine? we have introduces different instruments, all intended to describe at their best the turbines behaviour. among all, as stated, the maybe more interesting for our scope is the q-h diagram (QHd o QHp(for plane)). in fact it gives us the possibility to understand in a view all the different flow-head situations we can go through, and decide how to move and where to go according to the situation.
this section will be divided in the subsections:

1. before the idea of working point will be introduced: when talking of a point make sense, how it is determined, what to care about this; then an insight on the concept of head pressure and the relation between Q and H parameters, and concerning problems, is presented.

2. in thi second part we will try to understand where are we going to to place the working point, which are the interesting zones, which are the forbidden ones, what happens in each of them, and how we can go arrive there.

5.2.1 Working point stability

inlet conditions: how can visualize them? before starting to look for a suitable working area, is good to have well in mind the difference between the inlet flow characteristics and the working point: when we have a fluid flowing in a pipe, we can easily imagine the flow, Q. but what about the pressure head? if we have a free flow situation, such as for example a pipe that connects two basins at atmospheric pressure (AP), with no regulation element on it, we basically have no pressure head on the duct. the pipe is at AP and the water flows freely, as it was a river. we start having H in the moment we introduce some obstacles to the flux: in this way some pressure is created and we can start to talk of H.

open and closed systems but how is this pressure distributed? since pressure is created by gravity, it depends, in an open system (connected to the "external world") by the relative position of the single water particle with respect to the free water level, at atmospheric pressure. [1] in case of a

[1](for sure many more factors also affects a moving fluid pressure value and distribution, from velocity to friction and fluid regime, but here we just want to give an idea to explain the working point concept)

closed system this point does not exist and we will have a constant pressure in all the points of the closed area.
now, a penstock supplying a pat is a closed or open system? it can be both cases: it can be a closed one, such as a WDS that is formed of different pressurized zones, or an open one, as in case of a whatever free level basin. in the first case no problem: processing fluid with our pat we will reduce the pressure in the upper zone but this value will stay more or less equally distributed in the zone (and probably instantly refilled by some upstream apparatus controlled to keep this pressure value constant). but in the second one we will have a pressure gradient, diminishing from the maximum on its lower point (the pat in our case) to the atmospheric pressure.

pats and pressure problems but we like this pressure gradient? and we want to operate with our penstock pressurized or not? the answer is for a specific pipe the best thing is to operate always with the design situation. if it is constructed to work with no pressure, then we cannot pressurize it, and vice versa. so, since we want to generate electricity from pressure we will always need a pressurized part, at least the final one [2]. and this part will need to stay pressurized, always. why? this is a negative situation for two main reasons:

- mechanical stress on the pipe;
- fluid mechanics problems: in this situation could happen that a part of the pipe is not fulfilled with water: some air could enter the flow, arriving in the turbine and causing it to work badly.

what this means for our system? that we basically have to *process the exact value of the pressure head at the pat height.*

generating and processing H this could be not intuitive at first. to figure it out let's think about a practical example shown in fig. 5.2. is a situation of two no pressurized water basins connected, placed at a different height (24 meters). at first water flows down freely and there is no pressure in the penstock. what happens if we put a pat at the end of the pipe? the available head of the system is of 24m and the pat will have its characteristic curve, crossing the system curve in point A: we go to work here, getting another flow value (approx 0.27 m3/s). if this Q value is acceptable for the

[2] this could connect the pat with a higher part that could be at atmospheric pressure

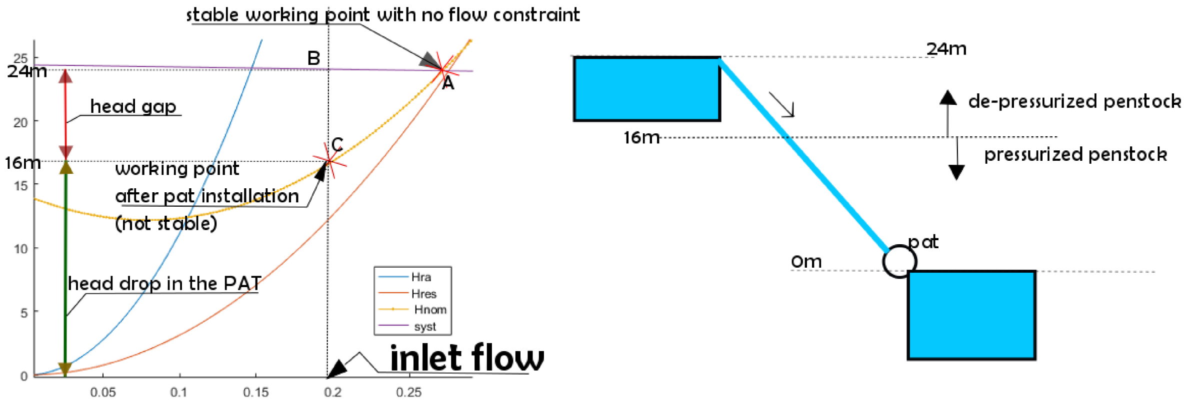

Figure 5.2: example to explain the concept of working point: with a fixed flow lower than the crossing point of system and turbine curve we cannot reach a stable situation: we would work in point C causing the head gap not to be generated, is saying letting the upper part of the penstock not to be pressurized. to reach a stable working point some control has to be introduced.

pipe size an the upper basin can provide it, we can work here in a stable situation and the whole head is processed: we have atmospheric pressure at the output of the turbine and the whole penstock pressurized. but what if the available flow was less than the "requested" by the crossing of the two curves (if for example the pipe is to narrow or the upside basin is almost empty)? in this case we would pass to work in point C: the cross point between the characteristic curve and available discharge value. is this a good working point? let's think about what will happen to the pipe: we would have pressure from the pat to more or less 16 meters higher. so only on the lower part, and then atmospheric pressure: this means a part of the penstock de-pressurized. this is the negative situation explained before, that we have to avoid.

solving pressure problems what can we do to avoid it? inserting a control. but how can we translate this limitation in terms of control? we can assume this as a rule: *we do have always to work in a point where the system curve crosses the turbine curve.* this means that all the available head is processed by the turbine, is saying our "obstacle" to flow generates enough resistance to flow to assure the whole conduct is pressurized.
to do that practically the two solutions of ER and HR propose a different but valuable solutions:

1. with HR we could place a series valve that, lowering the system curve, moves the point A, stable, to point C making it a stable working point.

2. with ER we can move the turbine curve upwards, until we reach point B, where the inlet flow condition is verified and also that of stability.

it is interesting to note that in this case with ER the head processed is quite much (24m vs 16m) than in case of HR, and this means roughly [3] proportionally much power, being the flow the same for the two situations.

representing the inlet point going back to qhp, how can we represent the free inlet flux condition? for what said a point would not fit: we can so always study the system and visualise the inlet condition depending the upstream situation: if a flow is imposed the inlet condition will be a vertical straight line corresponding to that Q, in case of a constant pressure it will be a horizontal one corresponding to the H.
we can then pass to the idea of a working point once defined our equipment and its effect on the system.

outlet conditions and what about the outlet conditions? for conservation of mass law we can suppose the flow to be basically the same, while the head will be the inlet head, without the head throttled, and the head gap in the turbine, that is the head represented in q-h curve. so when we work with no constraints it will be the atmospheric pressure, else it will be BP.

5.2.2 Working areas

runaway and resistance curves

starting from our mathematical model, we can obtain some curves that are really useful to the control task.

runaway the first of them is the RA, stating basically at which speed will go to work our turbine in case of no resistance load applied to the shaft: it is the curve our turbine will theoretically follow in case of fault of the mechanical connection. theoretically since there will for sure be some frictions (bearings) and inertias (shaft). also it is the case in which we will go to work in case of fault in the stator power supply for an asynchronous machine:

[3] at net of efficiency

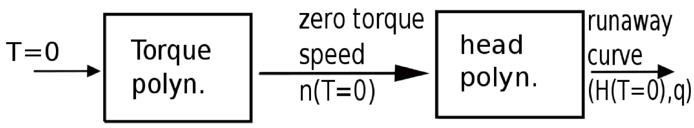

Figure 5.3: procedure to determine runaway curve

magnetic field at the air gap will disappear letting the rotor run freely.
the mathematical condition to obtain this curve is imposing the torque zero in our torque expression: in this way we can obtain, for every flow, the speed at which we have this condition. inserting this speed in the head model we obtain the curve we are looking for.

resistance the RC represents the condition of stopped rotor: $n = 0$;. how we can reach this situation? when the torque produced by the fluid is not sufficient to move the turbine. to figure out the meaning of this line we can imagine a basin at atmospheric pressure, discharging some flow through a pipe, at which end there is a pat. we can suppose to be in a situation of constant flow and variable head. with time the level of the basin will decrease more and more, and power produced will lower too. this will go on until a point in which there will be no sufficient pressure to move the turbine: the flow will stop and power obtained will be zero. we will then be on the resistance curve. moving downward on q-h curve, on this same example we will have, to have the same flux, to give power to our machine, and use it as a pump, pushing the water down.
to get this curve we just have to put the n=0 condition in the head model.
resistance and runaway curves are showed in fig. 5.4

power and working areas now that we have our q-h plane divided by this curve we can give a look at which of this areas are of interest in power production. the curves we have just deduced are really important since they are the two power zero curves. we have no power neither with no speed and no torque. and what happens to power over this two lines? first of all let's look inside: the area in between the two curves is where our turbine can work producing power: we have positive torque and negative speed (according to fig. 3.2) and we get negative power, that's say produced power. so this will be where we will have to be in order to produce electricity. but what happens outside this area? if we go below the resistance curve (RC), we will enter the condition in which we have to give power to move the water: we are in the second quadrant: speed, that was zero on the RC, now is positive and power

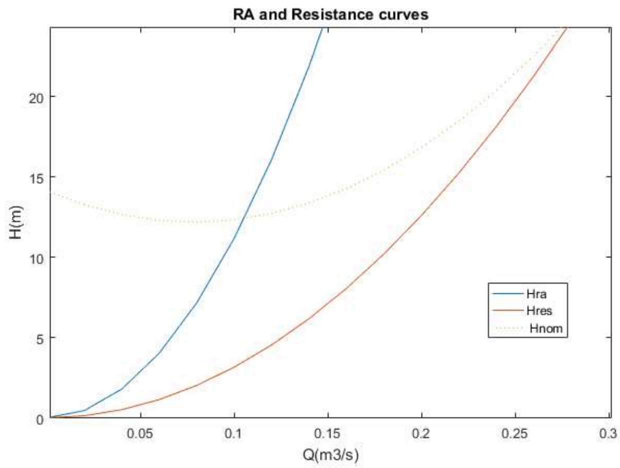

Figure 5.4: resistance and runaway curve

is positive too. we are interested to work here? we could be, for example in case we need to supply a determined flow to a plant or something, but not for energy production.
and what about going over the RA? in this case we reach a situation where torque is negative while speed remains negative: power is positive but in this case we are breaking. as before this could a case that we have to consider, but usually we won't go to work there.

other limitations for what regards working in between the two we have said it is where we produce power, but there are limitations here too: going up on the chart we will find the system curve: this represents the available net pressure head, and can't be overpassed: we can just work from here above, since this one is fixed from the inner flow characteristics. going down there are also limitations: we will have a minimum flow suitable for our machine. it is a parameter imposed by the construction of the pump in case of no control, and even if nothing bad happens to the pump if we work here, we will not be able to produce power. this point can be found on the chart looking for the intersection between the head curve and the RA one. this point can be moved by controlling speed: for an electrically regulated pat it will be much lower than in case of no regulation. this possibility is presented in the figure 5.5 with the dotted line. and from speed limits come another boundary: since, as said when presenting the electric machine, we cannot work at any speed, there will be tho areas, corresponding to the points that would require a speed higher or lower than the admitted by the electric machine, that will not be available for our control. all the constraints just stated are presented in fig. 5.5.

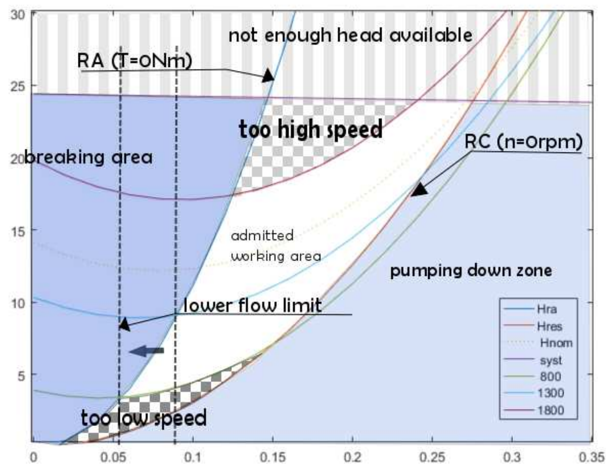

Figure 5.5: operation limits on head curve. the dotted line show how the inferior flow limits varies passing from the nominal operation mode to speed controlled one.

5.2.3 Regulations and parallel operation

now that we have delimited the region where to work, let's go to see how to move in this area. there are two main ways of moving, or better, to regulate our turbine, and are hydraulic (HR) and electric regulation (ER). they are two different way of actuating on the system but this do not mean we can use only one at a time: we will see that, as predictable, the most complete and flexible control will include both. but we will also analyse different situations in which maybe using the two is not necessary, or not preferable: every regulation imply a cost and could imply also a loss in efficiency of the system.

Hydraulic Regulation as seen when talking about valves, HR consist of a manner of regulating the inlet flow using some valves to deviate/stop the flux. so
it was historically the first regulation that have been applied for technological reasons (in '70ies, when the first pat installation where constructed, power electronics as we intend it nowadays almost did not exist [31]) and has different interesting aspects, and can offer a good flexibility. at the end it can still

be the best choice in some situations requiring simplicity and low investment cost.
a resumen of some of the benefits and drawbacks of HR is presented in fig.

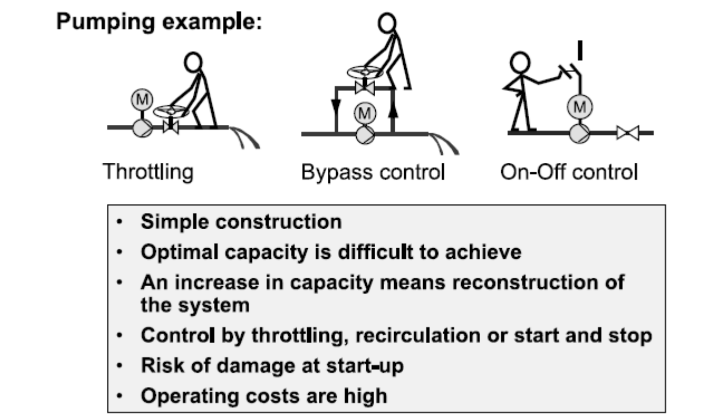

Figure 5.6: pro and cons of pump HR, from ABB technical guide n.4.

HR work dissipating energy and we will loose some potential power: on the q-h graph we can see it as we saw with valves: lowering system resistance curve: in particular bypass valve permits us to move to lower flows, while the series one to lower head. this is explained in 5.7 valves these could be driven manually, in case of an always constant working situation, or, really much better in order to get a flexible control, automatically, through some electronics.

Electric Regulation ER is operated through the inverter's control and consists of changing the frequency of the synchronous speed of the generator, in order to move turbine's head curve to reallocate the working point.
Variable Speed Control it is the best control method for many systems [22] and it is widely the most diffused in a market analysis point of view [22]. it simply consist in, instead of implying methods to reduce velocity starting from a higher point, regulating the generation directly. it is really well explained by the example taken from the ABB guide, in which the VSDrive is compared to the option of reducing the pressure on the gas pedal when driving a car and need to slow down to enter a urban area, compared with the idea of going on pushing the gas pedal and to reduce velocity pushing the break pedal at the same time, that is clearly counter-intuitive. this example explains very well the idea of variable speed control, but it is not exactly our case: here ER and VSC are not exactly the same thing. in fact in a

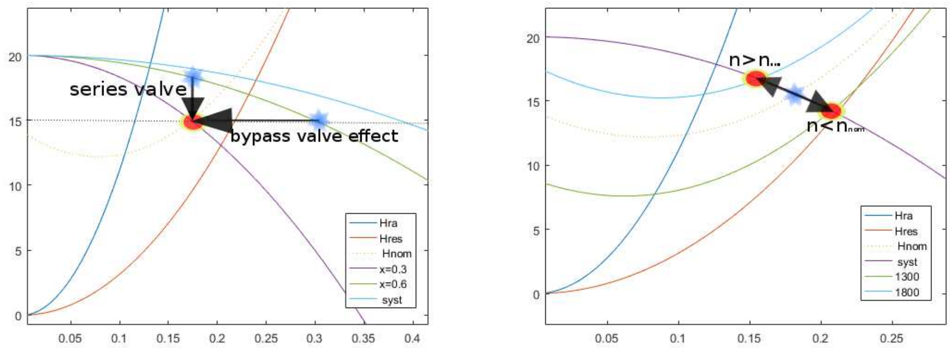

Figure 5.7: electric and hydraulic regulation: on the left HR is presented and the effet of series and bypass valve: starting from two different situation of q and h we manage to work at the same point on the nominal head curve; on the right ER starting from the nominal curve (1520rpm) going up to 1800 rpm or down to 1200;

Figure 5.8: varaible speed drive act as a car driver that reduces its velocity reducing the gas amount, not keeping it constant and braking.

pat system usually the idea is exactly the opposite: we want to brake an engine that must work at full gas. for sure, as proved by Hyypiä [14] is electrically convenient operate a pump at a lower speed than pumping strongly and then trying to recover the energy: the round trip efficiency will for sure be lower that that of the single machine. but that's exactly the point: we plan to work in a system where the gas has to be sent to the engine (to make another process work), and where at the same time we need to slow down our velocity to enter the urban area, and we try to do that with a pat. so how can ER help us? well in our case it can be seen as how much pressure, remaining in the example, we have to make on the brake pedal: this allows us to reach exactly the speed we need.
to operate ER whe so need a complete electric drive with an inverter and its control, the dc bus and, if we intend to sell electricity to the grid, the grid side inverter, to match grid requirements. ER increase performance, and is mandatory for application with strict constraints, but at the same time this equipment costs, could cost higher than the pat's itself. so the worthy of adding ER to our plant should be evaluated in every case.
talking about moving on qh graph we can now move up and down the characteristic curve of the turbine, in the speed limits of the generator. in fig. 5.7 are shown bot HR and ER.
regarding ER we have to say that adding elements to the system implies summing inefficiencies and this also has to be taken into account when evaluating the best control set.

parallel operation an effective option, that could extend the operability of an HRed only system is the option of putting more pats in parallel: they could be of different size or of the same size, and this can extend a lot the system range of operation, giving us the possibility to play with the different sizes to find the most suitable working point. in this case we can compute the overall flow as the sum of the flow in the single pats, while the pressure head will remain the same, exactly as it happens to shunt resistances, with voltage (H) and current (Q). this operation mode was yet known in the '80ies [6], as shown in fig. 5.9.

5.3 tasks limits and goals

we have stated our weapons, and now is time to focus on which are our objectives: ok controlling, but the most important thing to keep in mind when designing a control system is: what we want to obtain from this control? for sure we want to get all what can a pat can give us: we want to take profit

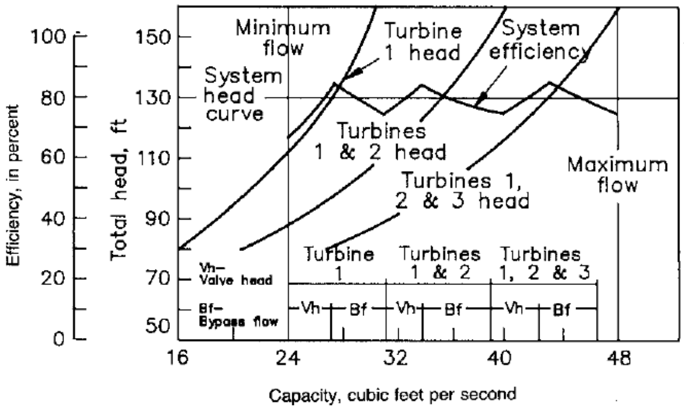

Figure 5.9: from Power engineering '82, parallel operation of different constant speed pats.

of our machine that we have paid and accurately studied. but take profit in which direction? for sure in energy terms, and clearly in economics ones. but it is not that easy as it could seem: if it was just about working always at maximum flux and head, maybe no control was needed. the truth is that a good control will try to match exactly this simple objective of taking out more energy as possible from our system, but we do have to care about limitations, and, especially, about how to get it. what it means taking the highest profit? it is not just about working with the higher flow and head, since there is the machine efficiency in the middle. so to perform a good control will mean taking in account efficiency of the machine in different working conditions, considering various physically acceptable situations and determine the best working point. so we have to define a sort of guideline of our doing: P.Garay was talking about the "take what you can" [6] philosophy for pat control. this one does not need explication and is for sure the pillar of this work, that try to extend this idea to the more complexes situations of HR and ER together; but we will not limit to this one, taking in account other situation in which other constraint could make us adopt other criteria for choosing how to operate our pat: three main different situations could occur:

1. take what you can: this will be applied to all these situation where almost no constraints or limitations are presents on the output of our system: the example to explore this situations is that of the waste water treatment plant in five fords: it is a plant where the flow characteristics are determined by the users of the WTS, but water is then thrown to a river, so no limitations are there downwards. sure, there is the

limitation of processing all the incoming water, but this could be easily managed with a bypass valve, allowing us to reduce the incoming flow if needed; so in this case we will try to maximize the power produced, taking all the energy we can from the incoming fluid;

2. fixed instant power. this is the case in which a pat is installed to serve a specific application, was a little machine operating some function in an agricultural situation where no grid arrives, or was it a domestic user. this last situation will be studied, in which a little water reservoir is designed to be kept in an elevated position (e.g. in a loft) to store the energy produced via a photovoltaic (PV) plant. in this situation our pat have to produce exactly the power demanded by the user, and the philosophy have to change: we do have to produce exactly this amount of power, and when a lamp is switched off, we have to adapt. so we will adopt other strategies: such as choosing the situation that allows us producing that power consuming as less water as possible, to minimize the dimensioning of tank, or to take the smaller flow in order to minimize pipe sizing.

3. fixed outlet requirements. is the case of the PRV substitution and is the one in which we are less free to operate: we will see that only one possible working point allows us to match the characteristics demanded for example by a WDS users downward respect at our pat. in this case we go back to the take all what you can philosophy but intending it in another way: of producing exactly what it is allowed by the systems, that is saying our control will just have to calculate how to generate the fluid specifications, and power will derive from this;

Chapter 6

Implementation

in this chapter we enter directly the problem of controlling a pat system. before passing to analyse one by one the case stated, we need to understand which of the listed instruments best fit for our goals and how to use them in best way. the idea is to:

1. explain some tools, derived from the mathematical model;
2. check the math limits and shape them to our problem;
3. try to apply the most suitable of them to the different possible situation;

6.1 Tools

6.1.1 MPP

the first powerful tool that will help us in determining where to go to work in order to match specifications and produce maximum power at the same time is the Maximum Power Point curve (MPP). it is a curve that tells us for each flow (or head) which is the corresponding head (flow) that can maximize the efficiency of our machine. so, with this curve we can, known the inlet flow, for example, determine the working point maximizing the power produced. (that, as stated, will be our objective in two fo the three main cases).
to determine it we can start from the math: the curve of power produced at each flow rate, will be a curve with a maximum, that is the point we are interested in. in this point the derivative will be zero and a specific value of speed will make us work there. so, deriving the power polynomial and resolving it, we can get the speed that gives us the maximum power for each flow. given this speed, inserting them in the head polynomial we get the desired curve. this procedure is explained schematically in fig.6.1

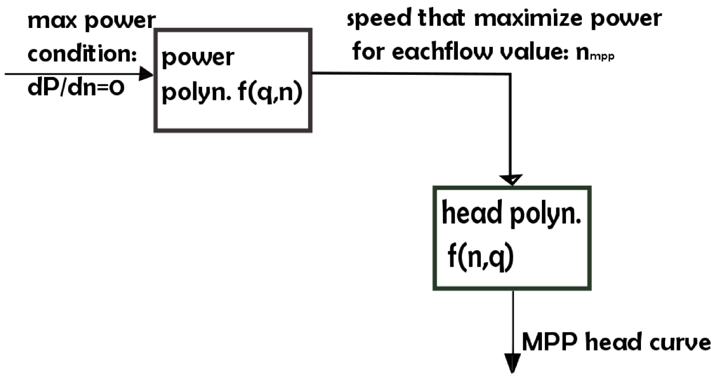

Figure 6.1: schematic of mpp curve calculation from polynomial model

the mathematics results:
solving

$$\frac{dP_t}{dQ} = k_{p1}Q^2 + k_{p2}nQ + k_{p3}n^2 = 0; \tag{6.1}$$

we get

$$n_{mpp} = \frac{-2k_{p2}Q \pm \sqrt{2k_{p2}Q^2 - 4 \cdot 3k_{p3}k_{p1}Q^2}}{2 \cdot 3k_{p3}}; \tag{6.2}$$

. inserting this speed values, with the Q values in the generic polynomial head model we obtain the MPPcurve, that results as in ffig. 6.2

we can imagine this procedure graphically in this way: for a given flow the computation of power for each speed means computing the power curve shown on the left in fig. 6.3: the highest point in the plane corresponding to each flow value is the MPP for that Q and tells us the speed value. given speed and flow the point is univocally defined on qh plane and we can identify it on the qhpower graph. an example of this (on the 3d power curve that will be calculated following) is shown in fig.6.3.

6.1.2 speed surface

moreover, looking at our power polynomial 3.7, we can see that we basically have three variables: H (hidden inside Q), Q and n: head, flow and speed. fixing two of them the third will be determined, and an interesting combination that we still have not considered is that of fixed head and flow. if this two parameters are fixed we automatically obtain a speed. which speed is this, or better, which is the meaning of this speed? is the velocity at which we have to operate our turbine to obtain the fixed values of Q and H. or from another perspective it could be the speed we have to give as reference to our

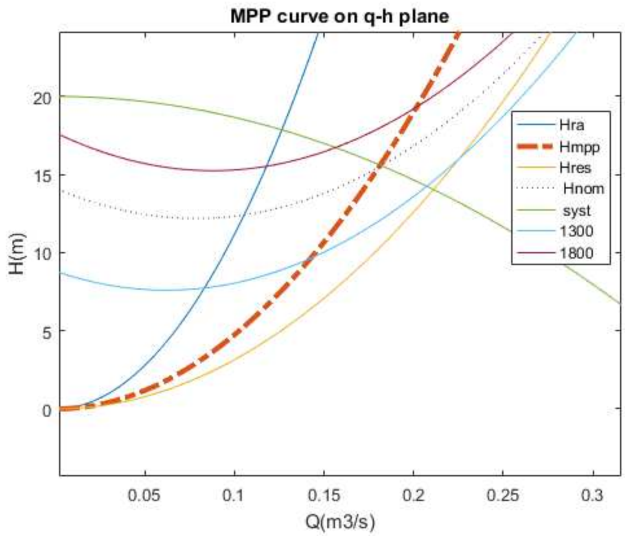

Figure 6.2: MaximumPowerPoint tracking on qh plane. in the specific case plotted the working point is exactly on the MPP curve and correspond to nominal speed. but as can be seen for higher flow values we reach MPP for higher speed and v.v.

system in case we have a fixed inlet flux with determined Q and H and we need to leave this unvaried. so for each point of the qh plane we obtain a speed: this allow us to move as we want just varying the velocity reference. we can represent this as a surface as shown in fig.6.4 . to obtain this picture we have simply to calculate for every (Q,H) couple the relative speed.

saturation it can be observed that, as intuitive, crossing with a horizontal (parallel to the q-h) plane the surface obtained, we get the head curve for the speed corresponding to the plane. also we can observe that the theoretical value of speed calculated wit hthis method have to be saturated at the maximum (and minimum) speed accepted by the electrical machine. this speed is variable and even if the induction machine is quite flexible and could accept quite high deviation from the nominal speed for transients [22], at the same time we cannot imagine to work a regimen at speed too different from the nominal one. but if we stay under a $\pm 20\%$ of nominal speed variation we can perfectly work [22]. in fig.6.5 an example of a saturated curve is shown: the speed limits and the resulting curve saturated.

low limit: what to do? it can be noted that the inferior saturation is setting speed at zero: this could led to a disambiguation: the idea is not

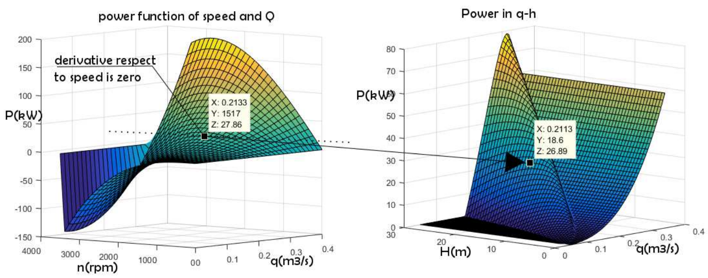

Figure 6.3: graphical mpp speed determination for a single point on the left (to have the curve we hae to iterate for all the Q values). on the right the corresponding point on qhpower surface.

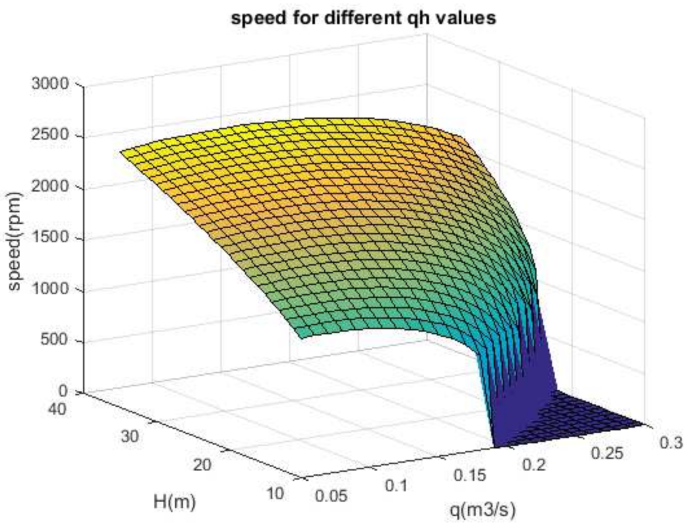

Figure 6.4: speed surface for evey qh value. it indicates at which speed we have to work in order to obtain the desired qh couple.

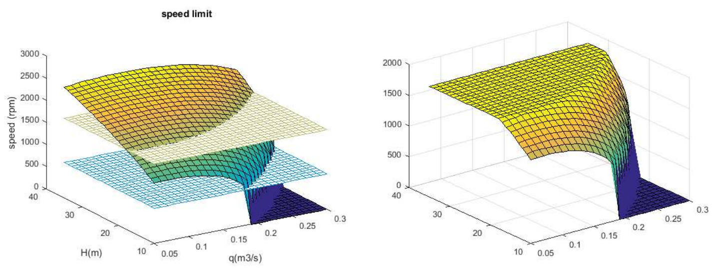

Figure 6.5: speed saturation: on the left an example of speed limit (800rpm and 1800 rpm) is presented, and the head curve resulting from the crossing of the two surfece is evident. on the righe the curve saturated.

forcing the turbine at zero speed. this is not like this: stopping the turbine would mean going to work at a different head-flow condition, while to have the desired QH level in this area we should supply electric power to push down the water. so where the reference saturated is zero in control perspective, we will intend opening the bypass valve and letting the rotor run freely until we go back to a suitable operation condition, and the zero reference will have to be coupled with a signal for the bypass valve to open.

6.1.3 power 3D graph

plotting the power for all the qh plane we get this surface, that is going to be really important to our study. some things are to be said about it. first of all a limitation: to obtain the final power matrix, we do have to solve a polynomial model for obtaining the speed corresponding to each of the q-h plane point. this is done by solving the second grade polynomial that results deriving power model. doing this we have to face a mathematical node of imaginary results due to the not real term under square root. this means we get incorrect results in a zone of the working area that we are not interested to: the area over the resistance curve. on this curve, as said the speed is zero and power must be zero too. how can we face this mathematical problem? one idea could be saturating this region, but it is quite complex and would have resulted really inconvenient doing it every time. so we will later one use this curve always reminding that this part of the curve, that will never interest us, is not to be taken in account. in fig.6.6 a saturation is presented, with its limitation, to give an idea of how the real curve of power looks like, and then a typical situation, with the invalid area marked.

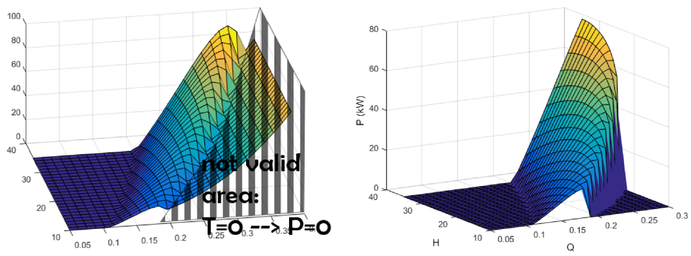

Figure 6.6: power 3d curve on qh plane. on the left how the model plots the invalid area is underlined. on the right we can see how it should a saturated curve be: no power is produced below the resistance curve.

Chapter 7

Control solution proposals

we now can start to have a look at the different situations that we can go through when planning to install a pat system. the three main situation are the ones already stated at the end of the Control chapter, and differ basically for the limitation that we have to face with when writing a control logic. we will see two main cases:

1. constraints imposed on the flow variables;

2. externally fixed power production;

for both we will start trying to depict the real situation to which they refers, then giving a theoretical look in order to develop the idea of control that is lastly mathematically developed and implemented.

7.1 Case 1: Fixed constraints

The first we go though is the case in which we have to face with external constraints on our flow conditions: the two flow variables, Q and H, are somehow fixed from external limitations that we, as designers, have to follow. different combinations of limits can occur at the same time: inlet and outlet restriction on one or the other or on the two at the same time can overlap. we will so have to first have a look to which are the most common situation, when they can happen, and why, and then try to consider ll the possible to situation to offer a solution the more complete and flexible as possible.

a real situation let's start with the most strict case of fixed flow and pressure head. first of all: is it a real case? and where can we get through this one? well the answer to the first question is positive: it is quite a common case. the first and king example of this situation is the case of the

Water distribution systems: to manage a water grid we do have to keep both pressure and flow under control and if placing a pat could be a good idea to reduce excessive pressure, at the same time we need to provide the requested flow and/or pressure at the exit of our plant. and the amount requested could vary, or better for sure will vary in case of WDS, during the day and the year. so for example in this case we need to design a flexible system, that can accept various couple of Q and H as inlet and that can provide the variation asked by the system regulation. the best case would be that of the pat thought as an actuator of the WDS control, but as an "intelligent slave", that has its own internal rule to maximize power in every situation requested by the central control system.
other possible examples could be all the plants where an industrial process is planned downstream with respect to the pat: such as if it is used as a pressure reducer to separate a higher and low pressure zone, or when it is thought as a flow regulator for a process that has requirements on inlet flux (pat's outlet flux). this last examples suggest us the existence of sub-cases: that of constant flow or head only required, that could be slightly different from when both are determined. we will so give a look also to this cases.

sum up of the objectives the various case could require different instruments that we can need or not, so a previous pook at which components to choose for a this kind of installation is presented. then, since having HR only or ER only is a possible solution in some of this situations, is studied in order to see a control strategy suitable for each circumstance and try to compare the different solution.
to sum up in this section we will analyse the case of:

· variable inlet parameters;

· fixed outlet constraints;

and we will see:

case	**regulation studied**	
Q=fixed, H=variable	HR (with or w.out bypass)	ER
Q=variable, H=fixed	HR	ER
Q,H fixed	HR + ER	

Theoretical study of the case

dividing q-h plane ok we can finally go to our qh plane: where are we working? and how to translate the condition we have to the graph? having Q and H fixed means they will told us where we hae to work, and our system have to be prepared to work in each point of qhp. what this means? all the restrictions already stated have to be forgotten? luckily no. so we have to be able to move to work in each point and each point have to be included in the "working area" that we presented when introducing the control (fig 5.5). and if the system asks me to work in a point not included in that area? we do have to take this into account when designing the system: every system request must have an answer from the control. so also uncommon situations have to be taken into account, such as a pressure requirement higher than the available or a working point over the runaway condition. but the first thing to do is for sure to choose well our machine. choosing the right pat is the most important thing and will help us a lot in controlling it, making the strange cases rarely appear, and assuring a profitable behaviour. the theme of pat election is not treated in this work, since there are quite much good works on this, starting from Alatorre [2], and Williams[26], to the more recent Novara's[8] or Carravetta and Fecarotta [1] works.

which machine better fits this situation? but how the election modify the working area? there are really every kind of different pumps, with various shapes of the turbine's curve. designing an installation, especially in an already existing plant, means fitting the shapes of our machine to the plant. so the first thing we need to know and to consider is: where and how will this plant work? this means considering the maximum and the minimum values of all the parameters we are playing with. and evaluating data. considering the historical limits of the plants, added to the typical periodical (daily-weekly-monthly and or annual) behaviour of our system we can make an idea of where to go to work. in the case of WDS there will for sure be a high defined periodicity and probably there will be data available, and similarly for an industrial process, maybe even more accurate. in this case usually we will face with many informations, since if we want a precise control we do need them. and with this informations we can chose a pat which working area include more or less all the possible working points.

unrecommended but admitted zones as stated the goal of a system of this kind can be regulating before producing electricity, so this is the case in which we have to take in account the areas where no power production is possibile but that could help regulation. in some particular conditions the lateral zones (over the resistance or the runaway) they could be taken into account for working, considering the hypothesis of supplying power to the system.

forbidden zones lastly there are the speed saturation zones. can we work here? the answer, in this case is no. there is no way, if not modifying the machine. in this sense though there are some possibilities such as the idea of evaluating a different pole pair number stator for example, that could allow us to work in a wider speed range and cover more areas. but this would imply higher costs for the machinery, and would probably not fit the first idea of a pat system: simplicity.

to bypass or not to bypass? we are going to see that using a bypass valve improves the flexibility and the performance of our plant quite much. moreover has to be said that a bypass is mandatory basically in every case for two main reasons:

· *security*: having a pressurized upstream means whatever happens to the turbine we do have to consider a way to overpass it and let the flow discharge

· *maintenance* of the turbine: once again for whatever work we have to do to our machine we have to operate without flux;

· we could be required to furnish a lor of water at a time for *emergency* situation like a fire occurring near;

so the bypass is to be included at least in design. even though the first case presented is that of HR without bypass: is just a in order to introduce the method, and in any case can be considered as a case in which for some reasons we do not intend to use the bypass to regulate (e.g in case the bypass valve is a manually driven one and we use it only in the uncommon situation stated)

Control implementation of Case 1

so our main task is we have to be able to work in each point if the admitted area. how to get there? there are for sure different ways, and there could be

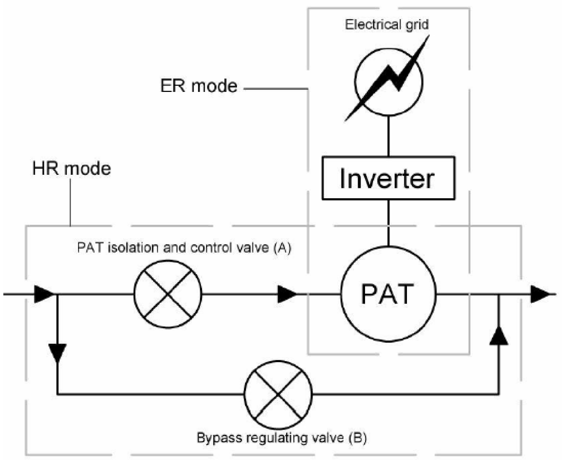

Figure 7.1: a schematic of the two regulations [1]

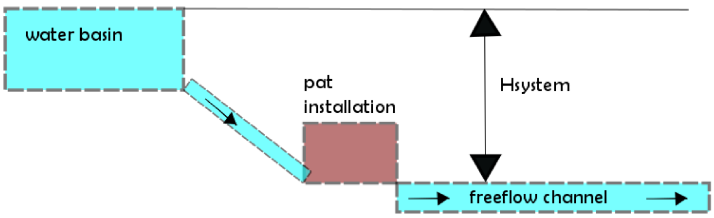

Figure 7.2: a generic example of flow regulation situation

one better then the others, or maybe one that best fit every case. which are our weapons? we talked about two main types of regulations, ER and HR, we will see both of them in order to choose the best.

7.1.1 Constant outlet flow: fixed Q

usually the situation of having to regulate Q is we have a fixed or known hydraulic potential (usually really big, such as a water basin) and we have to spill from it a little amount. like controlling a tap. it can be the case of a basin that supply a process. to figure it out we can think for example to a water irrigation system with no requirements in pressure (fig.). the flow so will be a consequence of our acting on the turbine an the valves. some different possibilities are presented following to face this same situation.

HR HR means work on nominal head curve, moving along this one with the help of the throttling ans bypass valve. in fig. 7.3 the admitted working point for the turbine of the example are shown in blue, and the relative flow regulating range is evidenced too.

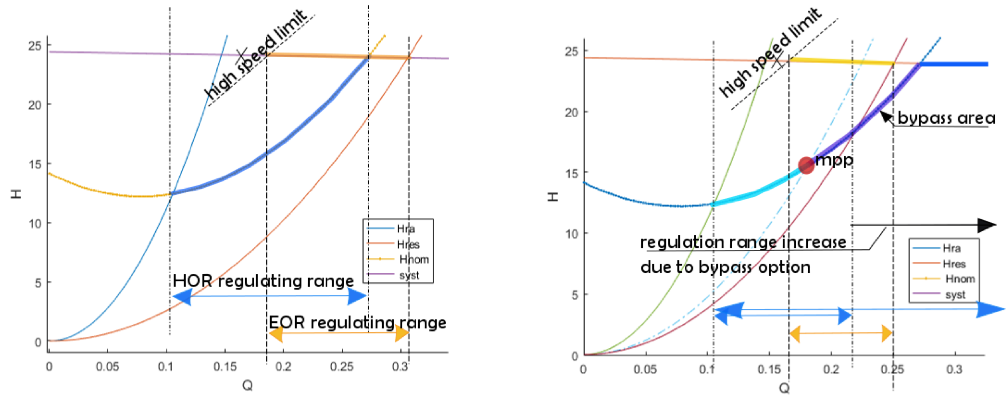

Figure 7.3: on the left a comparative of EOR and HR (without bypass) for flow regulation: we move on the system curve in one case and on the nominal head curve on the other, and the regulation range differs in the two situations, both in width and position; on the right the case of HR with bypass: the upper discharge limit increases to the admitted for the pipe. relative regulation range is also shown.

Series valve only in this case we have only one valve. how much we have to close it down? as explained when presenting valve's behaviour, in the hypothesis of linear valve, to obtain the relative valve opening we need to know not only the flow, but also the pressure difference, that influences Q, following the relation 4.1. but which value we take for pressure difference? we can obtain the same Q with different openings depending on the pressure difference occurring at valves extremes. since we said the working point have to be at the crossing of the two lines of system (including valves) and turbine, the head falling on the throttling valve must be the difference between the system available head and the H the turbine needs to process the Q we want. so we have to compute the turbine head and then for difference the head on the valve. finally we can obtain the desired variable:

$$x_{refseries} = \frac{Q_{fixed}}{K_{vmax_{series}} \sqrt{\frac{H_{syst} - H_{turb}}{\rho}}}; \tag{7.1}$$

the process is resumed graphically in fig.7.4.

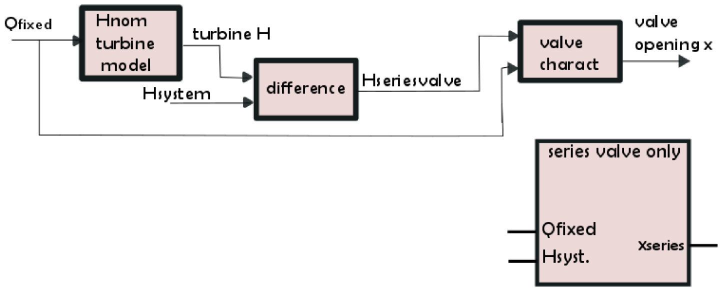

Figure 7.4: series valve only relative opening computation. bottom right the block as a box with its interfaces.

this is the value we have to communicate to the servomotor or the pneumatical valve governing the valve. in case we had no bypass valve we could stop here: we can work on the range shown on the left in fig. 7.3 and the only signal we have as output is the series valve relative opening. can be noted that to perform this regulation we do not need to know directly the value of the inlet flow. we just need to know the available head and then the flow will be a consequence of our regulation. it could not be different since for mass conservation law all what enters have to exit and we want to regulate the discharge. it will though be different with a bypass valve as we are going to see.

series + bypass if we have the bypass valve we can start playing a bit. we have to distinguish two situations depending of the required outlet flow Q_{fixed}:

1. $Q_{fixed} < Q_{mpp}$;

2. $Q_{fixed} < Q_{mpp}$;

in the first case it works as for series only valve: we throttle the excessive pressure to obtain the required flow and bypass valve stay closed.
in the second case is different: we can decide to stop increasing the flow passing in our pat, and let it work in the MPP: the flux difference will pass through the bypass, providing the exit with the required discharge.
to compute the throttling valve's opening we can use the 7.1 with the Q and H of the MPP (that we can obtain from the model, knowing previously the MPP).
for what regards the bypass, it works with all the H of the system since it is in parallel, processing the flow difference between the inlet and the processed

by the pat:

$$Q_{bypass} = Q_{tot-inlet} - Q_{mpp}; \tag{7.2}$$

where $Q_{tot-inlet}$ is the actual discharge, output of the flux-sensor.
the opening results from 4.1:

$$x_{bypass} = \frac{Q_{bypass}}{K_{vmaxbp}\sqrt{\frac{H_{syst}}{\rho}}}; \tag{7.3}$$

is to be noted that in this case k_{vmax} will be in general different for the bypass and the throttling valve if they are not the same valve [1]. in in fig. 7.3 on the right is shown HR with bypass and the relative increase in regulation range compared with the previous case.

no power production zones if we are in one of the first two listed zones, then it is not possible to produce power. what to do? can we go in the pumping or breaking zone? here it depends on the system request and we could chose to go to work there, as said, paying with some power the correct working of the system, or in other cases it will not be convenient (e.g. buying from grid is more expensive than stopping the process), or we could mediate to a medium situation of reducing/increasing the flux the more as we can remaining in the power production zone (e.g if the limits are not so strict, or if for some reasons there are some one-directional converters in the electric connection).
what to do then? in case of a flow requested too little for pat to work, a practical solution could be to close the throttling valve and use the bypass, that has a theorical minimum of zero and use it to regulate in this zone. the implementation is easy and we just have to use the characteristic law of the valve 4.1 using the Hsystem and the Qref.

$$x_{bypass} = \frac{Q_{fixed}}{K_{vmaxbyp.}\sqrt{\frac{H_{syst}}{\rho}}}; \tag{7.4}$$

for what regards higher flows we can bypass as shown: the case of a asked flow higher than the bypass is really unrealistic since, as said, usually the bupass valve has a really high discharge capacity that is of the order of the maximum flux allowed by the pipe. in the remote case we should simply let the system work with the two valves fully opened.

[1](and usually, as said, they will not, since the bypass have to be designed to face higher flows, such in case of hidraulic problems of uncommon requests from downstream eg. a fire)

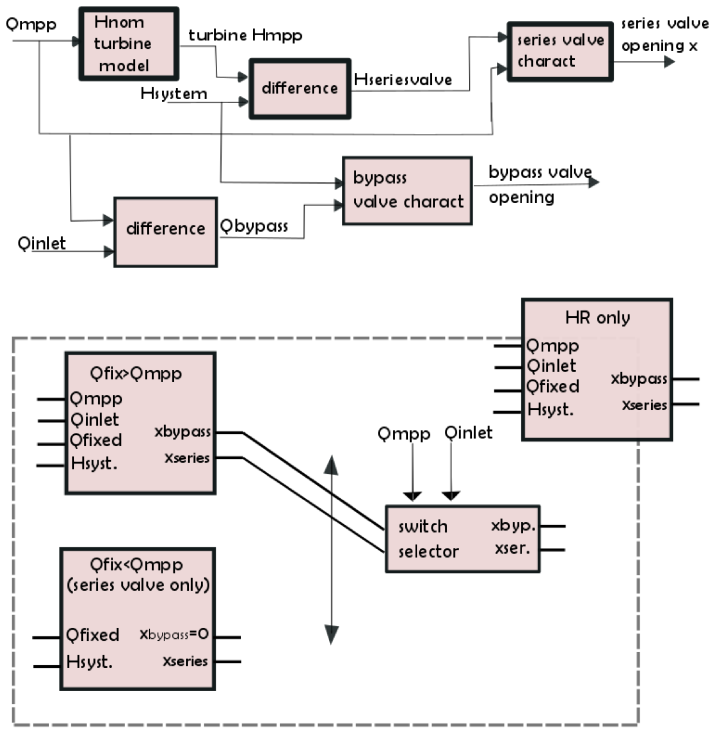

Figure 7.5: HR impementation with bypass option. above the scheme of the case of bypass workingbelow the scheme of selection with a switch selector that depending from the case (Qmpp¡¿qin) will let the desired signal pass to the exit an so to the physic world.

PID valve regulation another consideration, before passing to ER, is that flow regulation could be suitable for a closed loop feedback control with a compensator, in case for example of a single valve. in idea in this direction could be separate in two zones the graph as done before: the regulating area and the external parts. in the first ($Q_{min} < Q < Q_{MPP}$) regulating with a compensator our series valve, letting the bypass closed, while in the other controlling the bypass letting the series in one case closed and in the other opened to let pass Q_{MPP}. to calculate compensators we would need a system model, and its eventual linearity should be evaluated. this solution could perform a more precise control and should be considered for systems where flow requirements are really strict.

ER adding ER we immediately see we have now many more possibilities. we now can move with our head curve where we want (in the limits of the machine clearly) managing this way to forget the limitation in moving up and downwards: we pass from an 1D case, to a 2D situation, where we have a plane in which moving.

first of all let's give a look to the hardware: for sure the inverter is mandatory if we want to regulate in frequency; but what about the valves? as said bypass valve is mandatory, but we need it to regulate? and the throttling valve is still needed?

no valves what it mean working with ER but no valve at all? it means not being able to move the system curve, but only the machine one. is the opposite case of that of pure HR. we go back to a "1D" situation, in which, instead of moving on the turbine curve, we move on the system curve, changing the speed reference. the working segment is marked in yellow in fig. 7.6.

bypass only and suppose to add a bypass valve. what does it mean working without the throttling valve? for the regulating part is as without valves at all: we still move on that line. the enormous difference is that now we can extend flow range upward and downward, from zero flow, to ipe capacity. anyway it is still a quite a poor control situation, and if could be taken into account in some specific cases, it's difficult it could be a competitor of the other solutions. in the end the series valve helps us a lot, and to perform a good control we need it.

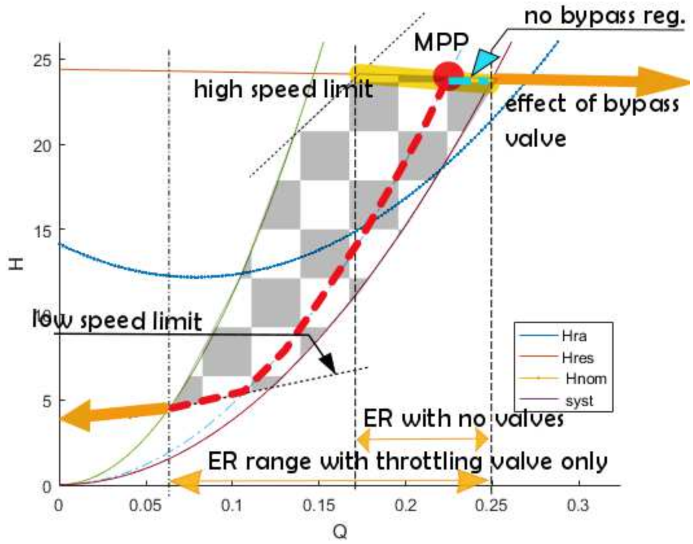

Figure 7.6: ER different options: we can see the effect of bypass on flow reg (extending upper limit to pipe capacity), we can see (squared area) where we can work with throttling valve and ER and (red pointed) the ideal way of performing flow regulation to maximize power. this line stops on MPP in case of ER and continues (light blue) for the case of no bypass valve.

throttling valve only for what regards the bypass we are in a similar situation to the one of HR: not only it is mandatory for the system, but also permits us to extend our regulation range upward theoretically how we want until pipe capacity. and not only, as explained when talking about valves and moving on qhp, we saw that bypass valve permit us to move horizontally (parallel to the q axe). but this could be performed, in working area, throttling and regulating in frequency. in the end, could it works a system in which the bypass valve can not be used for regulation? yes, it could work and well, with almost all the advantages of ER at the same time, but only in the small range of flows of the marked area of fig. 7.6. more, in this case, we have the possibility to move inside a plane, we can chose where we prefer to work.

we could so eventually take in account this solution[2] caring to take measures to face a possible increase of flow over maximum value. [3]

[2]a suitable circumstance could be when having a hand driven bypass valve and a really constant and predictable inlet flow.

[3]e.g. dispose an alarm to call somebody there to open the valve.(obviously in case of an installation in an always human-controlled area.)

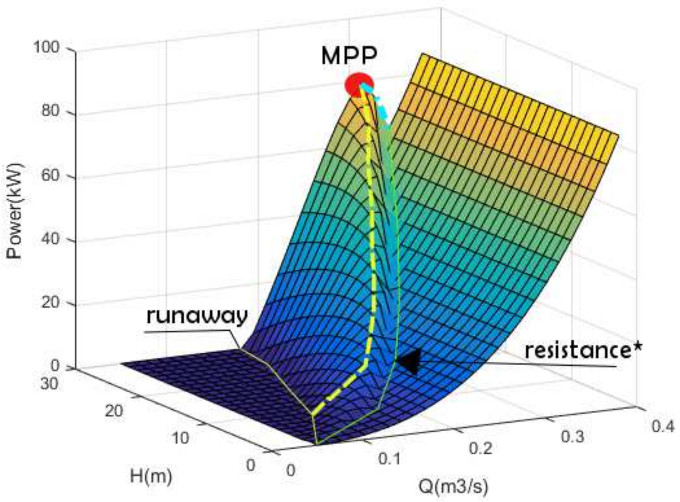

Figure 7.7: yellow dotted line is flow control with ER on power graph. on light blue the without bypass case. (as said when presenting this surface, resistance curve should be a zero power.)

full optional ER in the end as we saw both the valves are needed, especially considering a general case, where different values of flow have to be considered, so we will from here consider the idea of a system where HR and ER work together, that is the way to get the best from our machine: ER or HR alone for sure permits us to do something, but really poor when compared to the two together, that allows us to move on a plane, as said.
so, how can we move? how to take profit the most of this situation? if our first task is to regulate discharge, the second is to produce power. so is with this in mind that we can chose which path to follow in our moving up and down the qhp. how we maximize power? for sure moving on the MMP curve, that was build exactly for this purpose. so when this one crosses our area we go for it. in the other cases we can: stop on the low speed limit for lower flow; stop on the MPP, is saying, the point in which MPP curve crosses the system curve. to have higher flows we will bypass the discharge needed to match the requirement. in fig. 7.6 we can see this track marked with a red dotted line. is to be noted that in case of not having the bypass valve this last action can not be done: we will so follow the system curve until the maximum discharge point (blue dotted line in fig7.6).
the same control proposal is depicted in fig 7.7, where is clear how the higher available power situation, for each flow, is chosen.

implementation

let's now see how to obtain our system to behave as we want. we will consider directly the complete ER case, that is way more interesting.

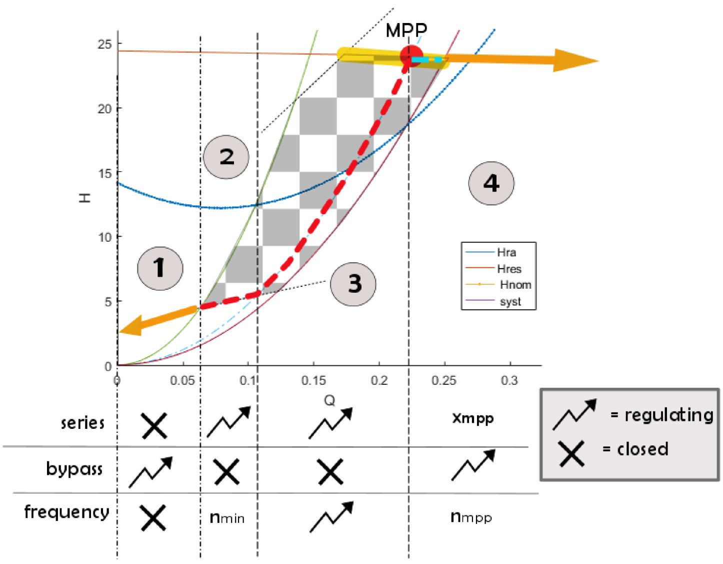

Figure 7.8: four distinct implementation zones can be underlined: for each we can see wich of the actuators is regulating and which is not: when a valve is closed an "x" is placed: is to note that for the case of frequency the x means we not need to regulate since no flow pass through the machine.

we can find 4 different zones, as shown in fig. 7.8. let's analyse them one by one.

1: really small discharge here we are asked a flow lower than the smallest admitted by the turbine. we can not do anything that is not closing the series valve and process the flow through the bypass valve.
to compute how to open the bypass valve we can proceed exactly as done for the same region in HR, as shown in 7.4.

2: low speed limit here we just set the frequency on the lower admissible for the generator and regulate with throttling valve. we have to compute the head gap in turbine at this frequency, rest it from the available head and with this value of H, and Q fixed obtain the series valve opening, as done for HR but now with a different speed value, that's the one corresponding to the lower frequency. it was shown in the upper part of fig. 7.5, where Hnom have to be replace with H_{nmin} and clearly the part of the bypass valve is not to be considered since it is closed, as shown in fig. 7.8.

3: regulating frequency here is when we finally can take profit hte most from our inverter. we do have to follow MPP curve, as said, how to do this? we have to compute, two things: a frequency reference and a relative opening for the throttling valve.
for the frequency, it depends from what we have. when calculating the MPP curve, we had obtained, solving the derivative of power curve, a vector of speed values (6.2), for each flow considered. we needed it to construct the head polynomial and obtain the MPPc. from this vector we can now obtain the speed reference, substituting in the same formula the vector Q, for our Qfixed value:

$$n_{Q_{fixed}} = \frac{-2k_{p2}Q_{fixed} \pm \sqrt{2k_{p2}Q_{fixed}^2 - 4 \cdot 3k_{p3}k_{p1}Q_{fixed}^2}}{2 \cdot 3k_{p3}}; \tag{7.5}$$

that we can easily convert to frequency: $f_{Q_{fixed}} = \frac{pp*n_{Q_{fixed}}}{2\pi}$; this correspond to, with the affinity laws, move the H curve of the turbine, is saying calculating the speed corresponding to that point. it can be seen graphically as finding a point on the surf of fig 6.4.
coming to throttling valve, we have to calculate with the MPPc and the Qfix the head that have to fall on the pat, solving the MPP polynomial for Qfixed:

$$H_{turbinempp} = k_{h1}Q_{fixed}^2 + k_{h2}n_{Q_{fixed}}Q_{fixed} + k_{h3}n_{Q_{fixed}}^2; \tag{7.6}$$

now we have to rest it from the H of the system and with this value and the Qfixed compute the opening.

$$x_{refseries} = \frac{Q_{fixed}}{K_{vmax_{series}}\sqrt{\frac{H_{syst}-H_{turbinempp}}{\rho}}}; \tag{7.7}$$

bypass valve here remains closed. a resume of the procedure can be seen schematically in fig. 7.9.

4: bypass and mpp this situation is the same as for the HR, as shown in fig 7.5. throttling valve is set to process the maximum power, idem for frequency, and the excess flow passes through the bypass valve. the only thing to say is that here the MPP could correspond, depending on the Hsyst, to a different frequency that is not the nominal one, so we will need the corresponding curve to compute the various output.

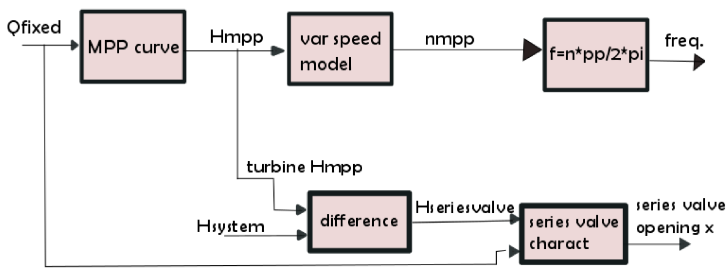

Figure 7.9: ER for zone 3: MPP curve and variable speed model are required.

parallel operation and technical considerations the proposed control routine is a general algorithm example. for sure have to be adapted to the system in which we intend to install the discharge control. also, is to say that, if lots of times demanded flows are more or less constant, is very common finding really variable flows too. let's think to every plant having to due with the forecast irregularity: a rainy day vs a sunny one, a spring rainy season vs a hot dry summer; this means a strong variability inlet fluxes. to face this gap, if water storage is not possible, a good solution is putting some different sizes turbines in parallel, so that we can be working profitably in many flux condition.
moreover, if in this case of weather susceptibility, plant safety has to be taken in account. an idea is to put a strong bypass in parallel with our plant. intended now not as the bypass regulating pipe, but as an alternative path for water, to be carried down and not processed in case of a dangerous situation for our equipment: a really strong rain or another limit case exceeding the usual values of flows.

7.1.2 Constant Head: H*= H_{fixed}

ok, let's now come to this other situation. reducing pressure. why could we need to reduce/regulate the pressure of our downstream system? a pair of example, as done before, to have in mind a situation when thinking about the control could be the following:

- an industrial plant has to discharge some water to a river, overpassing an obstacle in height on its path;
- the same plant has to discharge in a lake/water basin, and the exit point is placed underwater;
- a WDS in which a branch does not need the whole available pressure head. this could happen for geometric reasons (such as, once again,

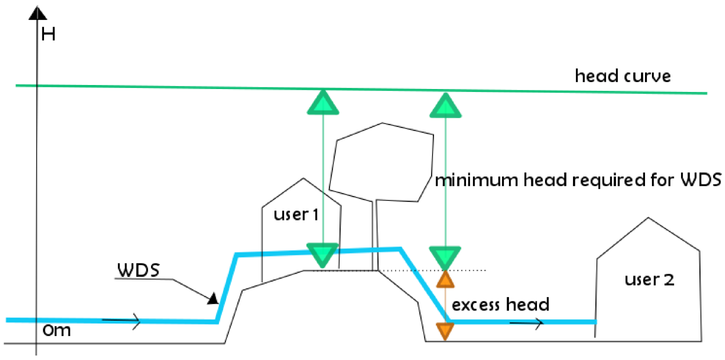

Figure 7.10: an example of pressure reduction situation in a WDS: at the top of the hill we have to provide a minimum pressure so we have to reach a H value that downstream is not needed if the only user is a similar one and at a lower level: the excessive H can be recovered with a pat.

higher H was necessary upstream to to overpass an obstacle, see fig 7.10, or in a plane area with water coming from uphill) or for system peculiarity (there are not high buildings or industrial customers requiring higher pressures in that branch);

in the first two cases we need a pressure, respectively, to overpass the hill and to face the hydrostatic pressure of water. but if we have upstream a much higher pressure it does make sense to recover the most of it. so we will have to process the difference between the inlet and the necessary to the fluid to exit the system. in the WDS case we need downstream pressure to operate it and to offer the service to our users.
these examples suggest us a characteristic of these kind of system: usually excess pressure does not cause downstream problems [4]. moreover, the upper limit is (then) not that strict: if the lower is mandatory (i need it to have a flow carrying out the water, or i need pressure so that water arrives to costumers), at the same time higher pressure will be absorbed by the downstream system without problems. [5].

BP and Head philosophy before approaching to the qhp, we have to think what does it means regulating pressure head. since we talk of pressure

[4] it could, for example in the case we use a PRV because we have a bad piping system downstream and it does not accept pressures higher than a limit value. but in this case we usually keep a high security gap, choosing the exit value far lower than the limit

[5] also because we are talking of reducing pressure: usually plants where a specific level of pressure is mandatory work at high pressure, and are fed by a pump/compressor, more than by a reducing pressure valve

we have to take in mind that we have to do with gaps. if upstream pressure rises, but downstream rises too, we ae working in the same situation as before. this casn see on qhp looking at how this changes can be represented. if we have a BP as our exit reference this makes shift the horizontal axe. as said, this makes that we work here with head differences, and not absolute values, to remain in qhp. but if who changes is the upstream H, then the system curve will shift up or downward. so if the two changes we obtain the whole graph to translate and no modifications occur looking at relative values. sure then the absolute exit H will be different.
how does the discharge affect this situation? the only effect we can see is due to the friction losses in the pipes, that could reduce a bit the H.

valves roles in the previous paragraph quite a great attention was done to the role of every valve and its possible absence. it was to give an idea of the role of every player, and to underline that, at the same time, if each of them is not absolutely indispensable, they are all really useful. from here on this part will be way shorter and we will just describe the role the various component take in each control. and if a specific case is really interesting will be underlined.
here we have that bypass valve basically regulates flow, while the throttling valve and the turbine struggle to obtain the desired head gap.

electric parallelism in primis the idea of th throttling valve letting pass flow without energy being taken off could result quite counter-intuitive. to better understand it we can think to a electric equivalent of our system: imagine the circuit of fig. 7.11 the key of the parallelism is comparing the pressure head H to the electric voltage V, and the flow Q to the current I. for what regards the element we can see the valves as resistances to the flow or to the current and the turbine as a voltage generator. the BP we have to match at the exit is represented as a voltage generator too, being a H constraint. resolving the circuit we can see how the current passing in the turbine branch is fixed by the throttling valve resistance and by voltage drop on the turbine. this two are related by the system and turbine characteristic and allow us to define the head/voltage gap over out plant. so the head/voltage drop over the parallel is regulated from the couple turbine+throttling valve and changing the value of the bypass resistance/valve we can determine the current flowing in bypass branch. the total flow is the sum of the two branches, one of which is fixed by the head-gap requirements, but the other can be freely regulated, making in this way the total flux controllable with series valve. we obtain this way a fully regulated system in which we can determine at the same

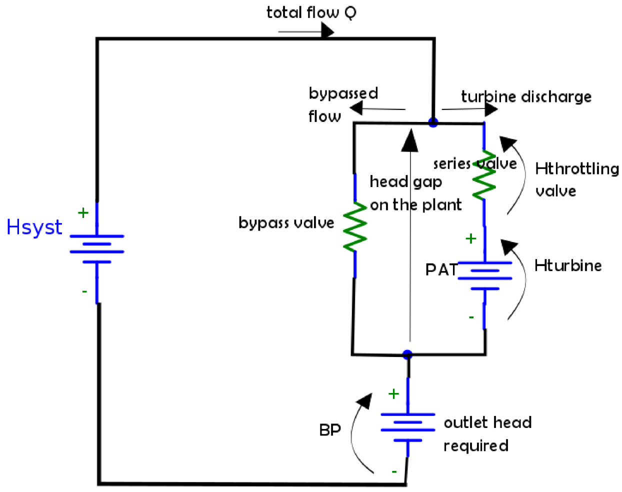

Figure 7.11: electric parallelism: voltage is associated to head, current to flow. the valves to resistances and the turbine to a voltage generator. system and the BP are head generator too, can be seen that the voltage drop over the bypass valve is fixed by the pat branch, while the resistance value (opening) of bypass valve determines overall current.

time flow and head gap.

implementation

so our task here is to adjust our turbine in order to produce the head gap between the inlet and the BP. in case of a fixed inlet H, and constant determined BP value, this means we just have to work in a fixed point. in this situation the turbine will be chosen such as this point will be at the cross of the freeflow system curve and the nominal turbine curve: in this case we would need no regulation at all. considering a general case we can have our pressure gap changing, moving the system curve as shown in fig. 7.12. so the cross point will vary and we have to regulate. the idea is always the same: looking for maximum power, that is saying try to follow the MPPc.
three different region have to be distinguished, as shown in fig. 7.12.

zone 1: let it flow in this area the downstream pressure required is similar to the upstream one: to obtain power we have to work at minimum frequency and process really little flow. we can do that, but the power produced will be likely near zero, as can be seen in fig. 7.13. or simply, we can just close our pat and let the flux pass through the bypass valve, assuring

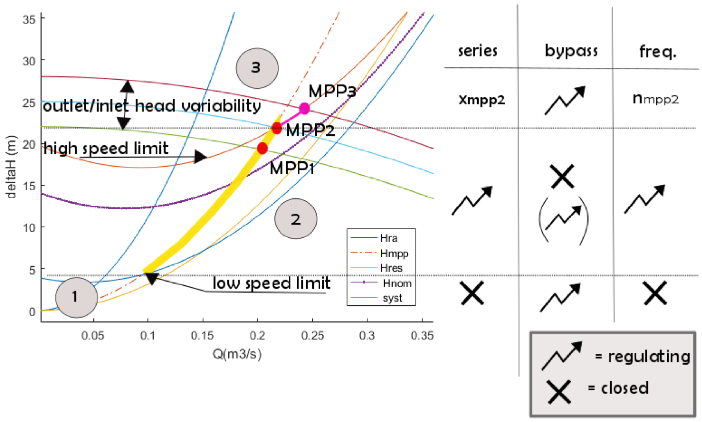

Figure 7.12: working areas for fixed Head control. in yellow the proposed control path, on the right the valve behaviour in the various situations.

to have enough output pressure.

zone 2: classic complete regulation here is the interesting zone for regulation: we can perform our control with throttling valve and our pat. moreover we can also regulate flow with bypass valve. is a really good control situation, really flexible. we can also match flow constraint and at the same time work with our turbine where we want. we can note that the more Hsyst increase, the more we have to rise frequency to follow the MPPc. we will arrive at a point where he maximum speed is reach (MPP 2 in the picture). here we can generally stop and start closing more the throttling valve, or follow the pink line. to decide what is better do, we have to look at the power curve and see where we get ah higher production: in fact it is not sure that the point MPP2 assure us a higher production, since the MPPc is computed for a rated q, while the two points we are comparing are for different situations. this will vary depending with power model coefficients. an example is shown in fig 7.13.

from the computational point of view, here we have two H as inputs: H_{syst}, the available upstream pressure, and H_{BP}, the reference downstream head. the first thing to do is obtaining their difference, that is the total head gap we have to fall in our pipes+turbine+valve system:

$$\Delta H = H_{syst} - H_{BP}; \tag{7.8}$$

now the system curve crosses the MPPc somewhere. from where this cross point is, depends our next move. if it is in the admitted area, this is our MPP, and we stop here; else we are in zone 3, and in next paragraph is

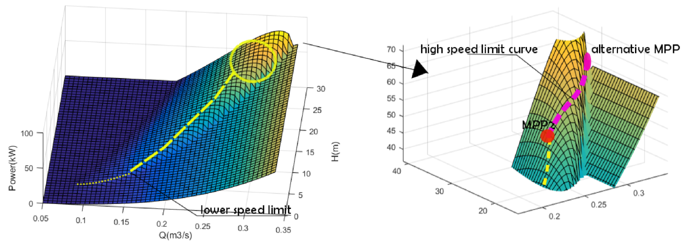

Figure 7.13: on the left the proposal control path is depicted, and low head situation is market with different punctuation. the higher point in-definition is then underlined on the right: the working point with high power production has to be determined looking a the power curve and coul vary depending from the model coefficients: it could be higher in the pink point, the cross point between system and higher speed curve, or in MPP2, the high speed and MPP curve cross point.

explained what to do. this point tells us the amount of H that have to fall on the series valve: since the point is allowed, and the system curve passes here, this means the whole system head falls on the turbine and we do not need to regulate with the throttling valve.
the first thing is obtaining the corresponding Q, equalizing the two equations of MPPc and system:

$$H_{mpp} = k1_{hmpp} * Q^2 + k2_{hmpp}Q + k3_{hmpp} = \Delta H - k1_{hsyst}Q^2 = H_{systeq} \quad (7.9)$$

$$Q_{mpp} = \frac{-k2_{hmpp} \pm \sqrt{k2_{hmpp}^2 - 4 \cdot (k3_{hmpp} - \Delta H)(k1_{hmpp} + k1_{hsyst})}}{2(k1_{hmpp} + k1_{hsyst})} \quad (7.10)$$

(taking the positive one).
now we have the flow, we can easily obtain from one of the two 7.9 the value of Hmpp, that is the H that falls on the turbine. the series valve is totally opened and we do not need to compute nothing. to compute frequency from the variable speed model we need the couple Qmpp and Hmpp if we have the graph, or for how we have computed it (as said for the fcase of flow reg) the truth is we just need Qmpp. in any case we have both and we can proceed with equation 7.5, substituting Qfixed with Qmpp.
for what regards the throttling valve we need to know the Hseries and Qmpp and once again we have both, so we can proceed with 7.7 with this two parameters.
about the bypass valve basically we do not have to compute nothing: if flow is not a requirement of the system we do not have to use it in this situation.

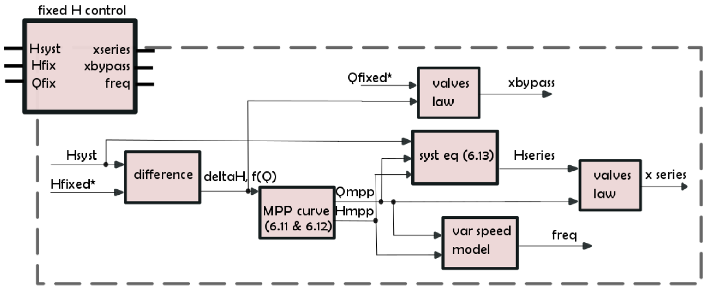

Figure 7.14: a schematic representation of the control for the case of fixed H. also Q can be regulated separately thanks to the effect of the bypass valve.

in case we are asked a specific flow, higher than Qmpp, we can just compute Qbypass with 7.7, using Hsystemeq and the Q difference:

$$x_{bypass} = \frac{Q_{inlet} - Q_{mpp}}{K_{vmax_{bypass}} \sqrt{\frac{H_{systeq}}{\rho}}}; \tag{7.11}$$

is to be noted that varying the Qtot we could theoretically recalculate the available head, since we should consider the eventual losses due to the flow change. this term is really small and can easily neglected.
in fig 7.14 a schematic of the control just presented is shown.

zone 3: throttling all the excess but what if the crossing point was not in the admitted zone? (is the case of the higher system curve, brown one, in fig.7.12) we have then to throttle down to a valid one. let's suppose we want to go to MPP2. in this case we have to do exactly the same procedure as before, but using maximum speed head curve (MAXSP), and not the system one. the cross point between MMPc and MAXSP is MPP2. we calculate our new Hmmp and Qmmp and with these we can go on with all the remaining parameters: frequency will altready be defined since we are working on MAXSP, while Hseries is the difference within the system curve H with Qmpp, and turbine one for the same Q, that is Hmpp:

$$H_{series} = \Delta H - k1_{hsyst} Q_{mpp}^2 - H_{mpp}; \tag{7.12}$$

if we want to go to work to MPP3, we have to find the corresponding flow resolving the system of system curve and MAXSP, and the follow.

7.1.3 Fixed H and Q

we pass now to the situation in which we have to regulate both the downstream pressure and the flow. it could be the general case for a WDS: the flow levels are regulated by the demand, and generally vary a lot during the day, with a certain periodicity. for what regard pressure, we have to match some limitations, usually assuring a minimum [37] pressure level to all users in every part of the WDS. but WDSs are organized in branches that could have different pressures, for managing or costumers needs. so we could have the case in which a pat is used as interface between two different areas, that have to remain at a certain pressures, different for the two. in general the pressure level varies quite much during the day, according to the flow request (as can be seen in fig. 3.4). so we have to consider a case in which a lot of flexibility is requested, both for flow and head values. as said head constraints can be considered quite much flexible, while regarding flow, if a user open a tap, we have to provide him water. to match such higher discharge variations we will have for sure to consider a big bypass duct, or better, to place the pat in parallel to a main penstock that could process the flow peaks. also the solution of placing parallel pats is interesting and could be a solution for this situation, and will be explained later on.

controlling we need a particular control for this situation? the truth is the control presented in the previous section (fixed H), already matches the goals of this regulation: we could regulate head and at the same time flow. so that one can be a good configuration, working well with almost all king of situation, especially in cases such as this one of the WDS, where pat will probably work with just a part of the main flux.

taking out bypass valve? a situation in which an alternative solution could be considered, is one with an external contour radically dissimilar. is saying a pat that works with an almost constant variables, but at the same time need to regulate them precisely. an example of a situation like this could be a pressurized irrigation system, where the pressure in the last branch is regulated in order to cover a certain area: slightly higher pressure to wet plants more distant, and lower for the nearer ones. in this case we could use a pat without bypass and control it just with series valve and frequency. to compute the regulating variables we should in this case move on the speed graph: having the two output flux characteristics as input for our model. it would be about moving to a point on the qhp, that tells us how to compute the valve opening, and then up to discover the corresponding frequency. this

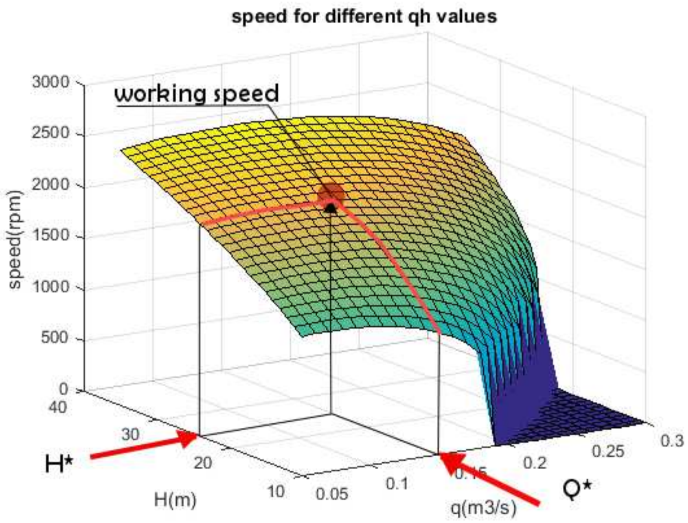

Figure 7.15: speed calculation for fixed Q and H and small variation range required.

process is explained graphically in fig.7.15[6].

7.2 Case 2: Fixed required power

The second big case we study is about power regulation and has output power as its external fixed variable. Flow variables are assumed here to be flexible and "adaptable" to the power constraints. for sure, planning a regulation in reality we will need to check their actual availability in terms of quantity: if we need a power the flow can not give us, we can have the better control but we can not overpass physics limitations. At the same time though we will give a look to both the two situations in which flow parameters are variable (e.g according with the water availability of a small river) or fixed (e.g. the case of having a little basin, with a fixed head gap and potentially infinite discharge values according with machine view).

again a real situation

As done before we start merging the theoretical situation with real life. When can it happen to have a external power output constraint? there is, once

[6]generator speed limitations are not considered in the picture but had clearly to be taken in account, as explained at the beginning of this chapter, see fig. 6.4

again, a specific key situation that can be used as an example, and is that of an isolated (in sense of not connected to the grid) user, with the turbine as (one of) its generator(s). Why should we care about a situation like this? first of all i will spend two words about the opposite case: why we should not? This second question may seem strange but in this historical moment, and where i am writing it does make a lot of sense. In fact the energy situation in Europe nowadays is quite critical, with a high demand of energy covered with fossil fuels. Not only, i mentioned geography also since it is quite common, especially in italy not to be that far from national grid, and to have the opportunity to connect to it. Is it convenient to do so? Today the answer is yes, it is. And the reason is because of government subsidies helping renewable energies, that make it more profitable to produce more than what you need and to sell it to the grid. Once again we have to look at today situation to say this is something environmentally "positive", since all the "C02 free" power produced would have, otherwise, been made, probably, burning some fossil fuel.

self-generation as a long term solution But this analysis is focused on nowadays. Developing technology just along with government behaviour, that usually are not reliable nor stable in time, is probably not a good idea, and subsidies are expected to be erased quickly, especially in times of "austerity" . This said, in a wider perspective, the idea of energy self-generation is for sure a win-win solution, providing users the independence from external factors, economical and/or political. Self-generation accorded to user needs is, i think the best idea of energy production. It means taking from nature just what you need, reducing the impact to the minimum, both from the plant point of view, with the idea of small turbines that need little head and flow, and from the river one: with discharge derived only in case of need, and otherwise letting the river flowing as much as possible as it would alone.

rural/mountain isle users This said we can so imagine how this is a big opportunity for many private users that could this way take profit for example of a little river passing in their area. It could be the case of many population in mountain areas, for single users but also for communities that could share the cost of low size turbine in some families and share the energy production that, as we will see in the simulation chapter, can easily provide energy for a bunch of families with reduced values of H and Q.
Then we can not forget about the situations where the possibility itself of

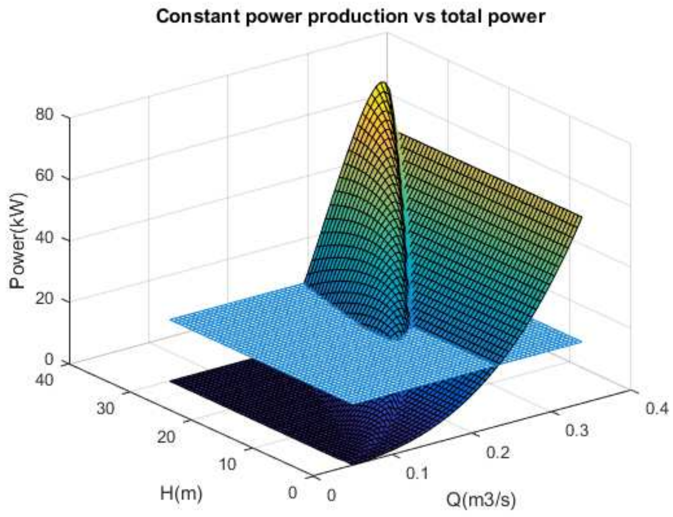

Figure 7.16: exampe of a constant power plane (horizontal), crossing the power curve. the intersection of the two represents the couple of values Q and H that can provide us the desired power.

connecting to the grid is not available: that is not a case so rare too. Even if in Europe everything may seem close to national grid, at the same time there could be limitations to the connections: Cables flowing in the air are bad to see and have a strong environmental impact, so that usually the mountain areas suitable for PAT installation may be placed in a Natural park, or in some places where connection is difficult for geographical reasons too.

reducing water consumption or maximizing efficiency?

let's pass now to the study of the system, to check out which is the solution most effective in order to match the just stated objectives. we said we have to start from a given power, to drive the system to produce this output our user ask us. what does it mean a fixed power? it is an horizontal plane in our power curve figure, as shown in fig.7.16. as we can see the intersection within the two curves is a line, and this line is the function representing the couple of values Q and H that, provided to the turbine, make it producing the desired power.

choose one value Does this make sense that we can have different solution that give us the same result? for sure, since the power is the product of the flow and the headgap, so we will have different combinations of the two values. but this means we have to chose one of this couples of valus, since we have to tell our control system a precise point. how we choose then? i think there could be two main philosophies in this direction:

1. water consumption reduction;

2. machine efficiency maximization;

the first speaks itself: it is for sure a good philosophy, especially when we talk of a system taking water out from a river: the less we take, the less the impact will be, in general, even if usually the difference in the amount will be very very small.
the second is the classical engineer philosophy and speaks itself too: it may mean using a bit more of water but at the same time using the machine closer to its design point means rising its life, thanks to the better working of all the mechanical parts.

are really different options? but coming to the implementation, we can se this two ides are at the end not that different one from the other. as we can see in fig. 7.17 we can individuate the point of smaller water consumption as the point more on the left on the constant power curve; for what regard the higher efficiency one, we can use the MPPcurve, and take the crossing of the two. [7]

looking at the two point on the figure, is evident how closer they are: we can consider the two tracks bringing us to the same point. that is for sure a good thing, since we have this way matched the two goals at the same time, and we have a value to be communicated to our control system. how to compute it will be the same: if following one or the pother way. we will follow the easiest and how to do it will be shown in the last section.

Control implementation of case 2

to implement the control we just showed means basically calculate the Q and H couple that represents the working point we have obtained in the previous paragraphs. once we have this point it is just about using, once again, the same structure explained in the part of the control for fixed external constraints. as we saw we have two easy of computing our point: following

[7] even if this is not perfectly exact from the mathematical point of view (the MPP is computed for each flow, here we are comparing different flow values and could be that for one flow value the highest efficiency is still lower than the efficiency for another flow): this implies a really really small error and could easily be accepted.

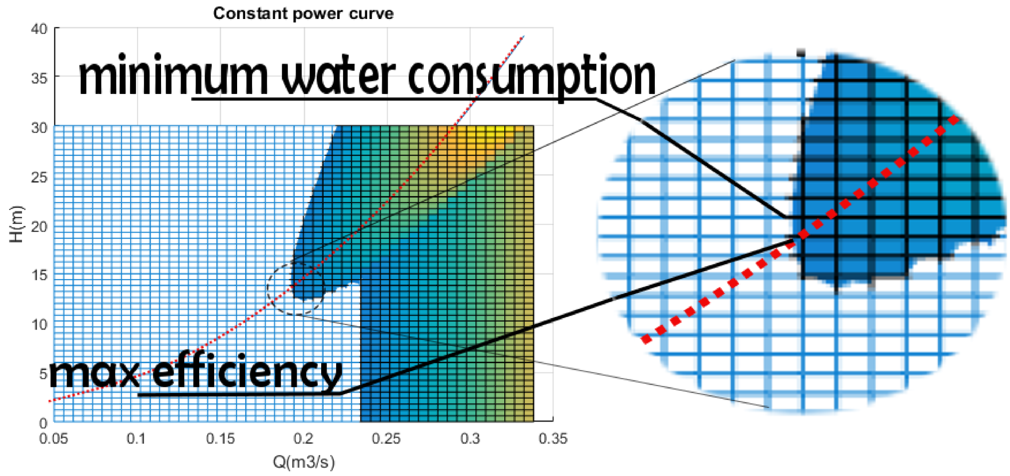

Figure 7.17: the two philosophies, of reducing water consumption and maximizing efficiency led to almost the same result: the working point for each power is so defined, matching the two objectives at the same time.

the minimum water consumption criteria, or the MPP one. the two will be shortly explained and then the first one will be shown a bit more accurately.

minimum water consumption criteria we saw in the theoretical study that the point found with this idea is the first point on the right on x axis on qh plane. this mean we can find it scanning our power matrix starting on the left, is saying for zero flow and see if there is some value for which the power produced correspond to our objective. the first value obtained will be our result. [8]

mpp curve criteria in this case we can get to the point in a different way: we can compute, with our power formula, the power produced for every single point of our MPPcurve, and then compare this to the power we need to obtain the point we re looking for (crossing a plane of constant required power with the line of power produced for mpp we obtain a single point). as said the point obtained in the two ways will be slightly different but basically the same.

[8] theoretically it should be just one value, the tangent point of the curve. actually, having the curve as a discrete sum of point, we will obtain a bunch of values, depending on the precision of our discretization. we can take the first one, being this one the closer to the MPP, but all could be considered ok.

7.2.1 minimum water consumption algorithm

as we just said we are looking for the first point we go throug hin our matrix scan. how to do this via software? the simpler idea and effective is doing it via a pair of for cycles, scanning the matrix for each flow value and for every H value and comparing the power corresponding to each couple with a precise value or, better, talking of a discrete point curve, with a range of values of the type: $P_{ref} \pm \Delta P$. the cyclic routine will result in something like this:

```
for q=1:ndiv+1
  for h=1:ndiv+1
    if Qg==0;
      Pref=Pmax(h,q);
           if and(Pobb-0.01*Pobb<Pref,Pref<Pobb+0.01*Pobb)
              Pff(h,q)=Pmax(h,q);
              Qg=q;
              Hg=h;
           else Pff(h,q)=0;
           end
     else
     end
   end
end
```

This program gives us the couple of values Qg and Hg that are what we were looking for, and that we can use as input (Hfixed and Qfixed) for the routine showed in fig. 7.14. the results of this is shown graphically in fig.7.18

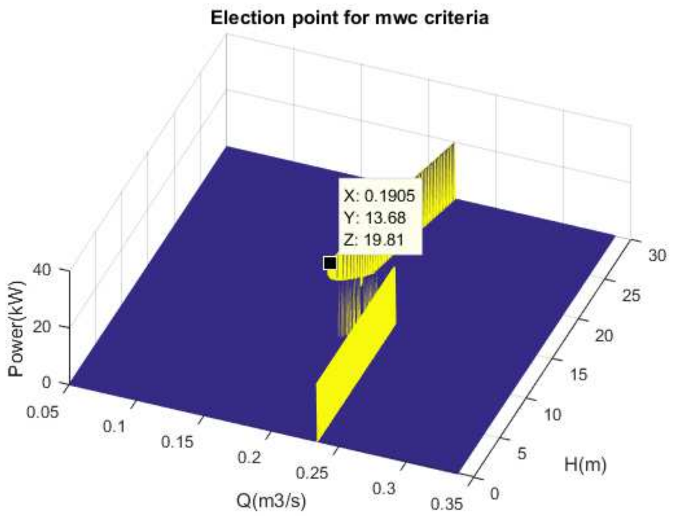

Figure 7.18: the routine proposed scans the power matrix giving the curve shown. if we add the condition of stopping when the first interesting value is found we will be given the point highlighted, expressed as the couple of values Qg and Hg. in this example, for a power of 20 kW we find Hg=13.68 m and Qg= 0.19 m3/s;

Chapter 8

Simulation

in this chapter we try to apply the theoretical implementation proposed to see if they really could work in a simil-real environment, is saying with variable and real like inputs. To do so some real data from WDS have been taken and the proposed implementation methods have been realized in a simulation environment. Good results have been obtained and this is the natural step before passing to implement the control on real machinery.
The simulation situation chosen is that of a pressure reducing valve. it has been elected since, as said, this one is one of the most common situation in which a PAT could be placed and one of the most interesting application of the control part since we have to deal with strong restrictions and variable parameters.

Simulink Simulink is the simulation environment powered by Mathworks. is a really flexible tools, with lots of examples and elements to be added. it does not need particular presentation, and have been elected for its completeness and for the possibility to interact easily with the Matlab environment where the previous calculations had been done. it works with a graphical interface of blocks linked by lines, as in the classic control literature.

8.1 Pressure Reducing Valve simulation

The first simulation we introduce is that of the first case study, so, fixed constrains one. the elected situation is that of a PRV, placed in a WDS. the reason for this is for sure that this is the main viable application for a pat system. moreover it is a good chance to apply the complete model, regulating at the same time both discharge, Q and pressure head, H.

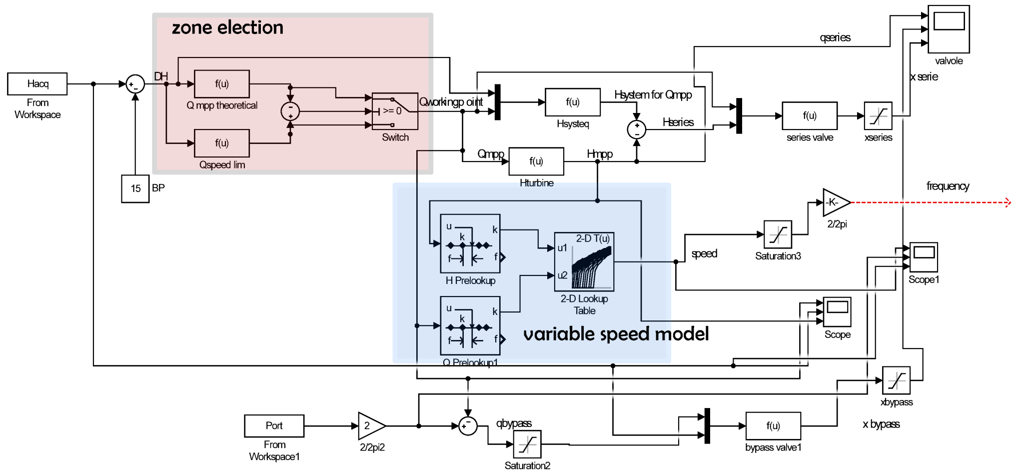

Figure 8.1: simulink model of PRV

8.1.1 PRV control Simulink model

the control scheme to refer to is that shown in fig. 7.14. it has simply been translated in Simulink, with the necessary adjusts. it will then not be explained once again from the theoretical point of view, and for this you can refer to the paragraph 7.1.2. we go here just to give a look to the technical implementation of the model. the model use is shown in fig:

The zone choice the first thing to do, we said, was to understand where we were working on the qhp. but we had not exlained how to do it. here come a proposal for this, that was used in the model.
to locate the working point we said we have to look at where the MPPc and system curve cross each other. if it was higher than the speed limit curve (MAXSP), then we had to throttle, else we could work there. the idea was in this case to compute the two crossing point:

- MPPC and MAXSP, obtaining Qsl;
- MPPC and Hsyst, obtaining Qmmp;

we obtain the respective Q solving the system of the two head polynomial, and the Q will be determinant: if the Qsl is higher than Qmpp, this means that we the working point is higher than our speed limit curve: that is true since we are crossing an increasing polynomial curve (MPPc). so the condition is:

- $Qsl > Qmpp - - >$ zone 3, we have to throttle and work on MAXSP, we will use Qsl as our Q;
- $Qsl <= Qmpp - - >$ zone 2, we can stop here use our Qmpp, and regulate in consequence;

Switch selector to construct this condition in simulink we have used the switch block, that permits us to chose which of two signals to let pass. we decide to let pass a discharge value, with which then we construct the whole system model.

The speed calculation for what regards the computation of the desired speed, the variable speed model of fig.6.4 has been implemented with the logic of entering a 2d graph as explained in fig. 7.15. to do this simulink permits us to take a matrix generated in the workspace. there is though to deal a bit with the so called "breakpoints": the range values in which the entering signal has to be placed. since for computation simplicity the matrix used was just a 26x26, we have a discrete model. this means that we have to enter the block "2D lookutable" with an integer, that we usually not have, since we enter with a discharge value of the order of few $\mu m^3/s$, and a H that is calculated by a polynomial model so is for sure a float value. to adjust this we need another block, called "Pre-lookup", that allow us to discrete our axes, creating for us the corresponding integer to enter the table. this means for sure loosing precision, and it is evident when simulating: when saturating for speed limit we get a speed value of 1770rpm vs 1800rpm of limit proposed in the theoretical model. that is due to this pre-lookup. it could easily be solved increasing matrix dimension.

Saturation for what regards saturation in speed, it should be not necessary, since for hw we constructed the model we should not get higher speeds. and moreover we could have used the already saturated model. in fact, we used the whole model and placed an artificial saturation, in order to being able to control the speed value proposed as a feedback control.
valve signal have been expressed to output a result in percent. they also have been saturated, since due to the imprecision of the valves coefficients, we get values higher than 100

8.1.2 Simulation data

coming to the simulation, since the idea was that of simulating a WDS plant, some data have been taken from the web of a typical daily oscillation of

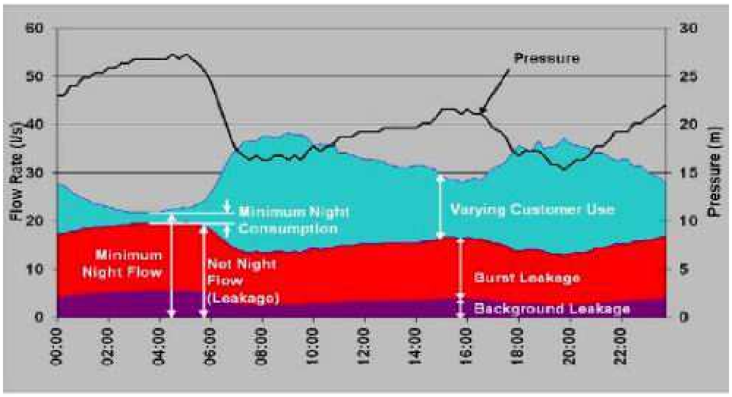

Figure 8.2: the WDS data, taken from altratecnica.files.wordpress.com-2013-04-perdite-pressione.jpg

pressure and temperature. the original data are shown in fig.8.2. this has been used as reference for the curve shape, and from this have been adapted the values to get the situation that could fit with our machine. in particular two cases are proposed:

1. "high pressure": H is doubled (we can read this values on the discharge axe in the picture) and Q also is doubled to fit turbine size; BP is set to 15m;

2. "everyday working": the H of the image is used, while Q is le the double; BP is set to 5m;

the first situation is more tricky from the control point of view and the valves have to work more: we work on the border of speed limit and our "election block" has to struggle with it.
the second situation is where we work in case of a well designed system: we get different flow values but the H fit perfectly our turbine and we always remain working in the admitted working area, in saying in the regulating range. here series valve never works and bypass only in the water discharge peak.
this two working areas are grossly shown in fig.8.3

8.1.3 Results

let's have a look to some simulation results. we will see how different aspects of our system evolves in a day long period. the transients are ot considered, since are not relevant in front of the simulation time. we will start from the

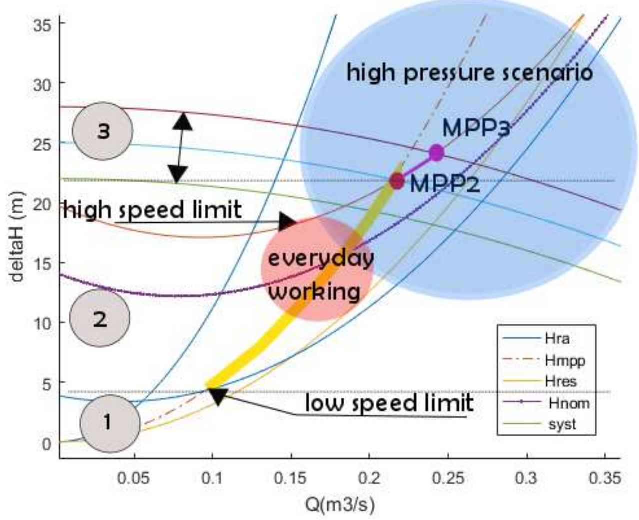

Figure 8.3: the two proposed scenarios on the qhgraph: everyday working, in red, simulates a turbine almost never crossing the working limits, while in blue "high pressure" is a more variable and complex situation.

physics of the system, passing to how the signals we generate comes and if they fits the system. lastly we will see a panoramic on power production and the energy produced, making some considerations. the two scenarios are presented in order and then compared.

Scenario 2: high pressure

as anticipated to simulate this scenario we used the pressure doubled: the maximum is over the 50m, and the minimum sets at more than 20m. the BP value has been set at 15m. we start with this that better explains the behaviour of the various elements at crossing the limit curve

System physics to analyse simulation results the first thing to do is to understand if the physics of the problem was respected. the inlet parameter are Q and H and they follow an opposite tendency: since they ae linked, when one increase usually hte other decreases. this can be seen clearly in fig 8.7, where we see they are almost specular.

Q and H looking at the turbine (fig. 8.4, the discharge, seem to follow quite a different direction: since here enters nly the flow we want to pass through the turbine we see the upper limitation, horizontal line), that corre-

spond to the Q at the cross point within MPPc and MAXSP: we decided to work here in any case the head was higher. so here throttling valve is doing its job and we work there, at maximum speed. this can be seen in speed graph: they have a really similar behaviour: that sounds, since moving upward in qhgraph means increasing flow and speed. always looking at Q through the turbine we see two regions where it lowers: they correspond to the moment in which we have a really high inlet flux and low head upstream. this may sould strange, since we process less fluid whene we have a lot incoming. but this is perfectly logical thinking that in this situaton we have low H: this means we can not work with our turbine where we want, but we have to respect the system H levels: we have to remind thatthis regulation is based on H gap.
Looking at H values (fig.8.5) we can see how inlet H is divided between turbine and series valve: it is the control logic: the sum of this two H term have to equal the amount of available inlet H, in order to work without pressure problems. This means that H value in the turbine remains constant at the max value when we have excess H, and lowers down when it lacks. the opposite tendency can be seen in series valve that provide excess head processing.

Actuators signals coming to the actuators (fig. 8.6), for what said, series valve works when we have high H to be reduced. whit lower H and a higher Q the turbine can not work with more than a little discharge. or better the turbine could work with higher discharges (such as in case the bypass was near its limit), but this would mean exiting the MPP situation.
bypass valve in this scenario is always working and has to process quite a lot of water, even if it reamins far from its limit as, as said in the previous chapters, this pipe has to be oversized in order to face eventual emergency flow peaks, due to weather or to grid needs or faults.

for what regard speed as already said it follows the turbine flow. this means working most of time at speed limit. this underlines th importance of choosing well both the generator machine and its speed limit: it has to be a working condition where the machine can work with no problem for long times: in this simulation we work for as long as 6 or 7 hours at this speed. and the lower speed we reach is higher than nominal. so the speed working range of this generator is quite well defined and do not need to be so flexible. starting from this we could imagine solutions as placing a mechanical reductor or changing machine or choosing a different turbine. so if in general an induction generator could easily fit the situation, this alternatives could be considered in case we see it efficiency is lower than predicted, of in general

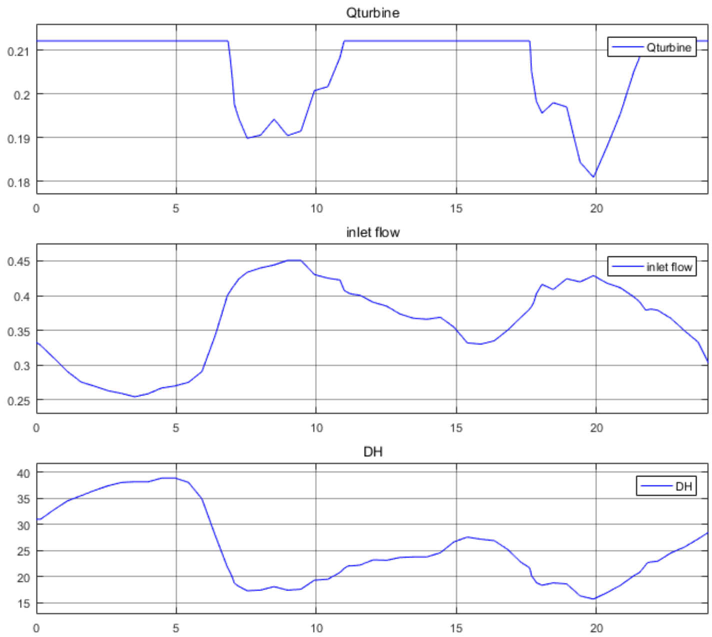

Figure 8.4: different flow compared: turbine flow at high top has an opposite tendency to the inlet discharge, this is due to the H availability to be processed that can be seen at bottom

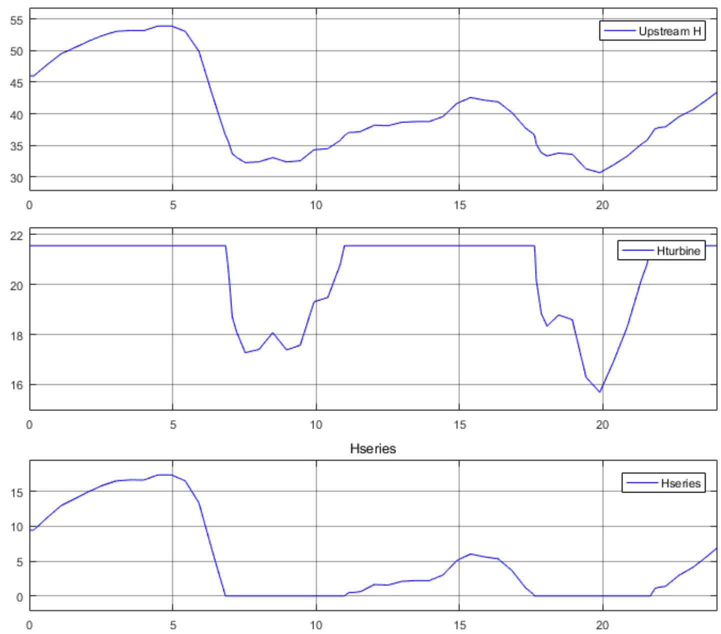

Figure 8.5: pressure head available (first graph) is divided between the turbine (middle graph) and the seires valve (bottom): high H means the turbine working at saturation and series valve working, at the opposite with low H values, we can see that no head falls on series valve: it will be fully opened

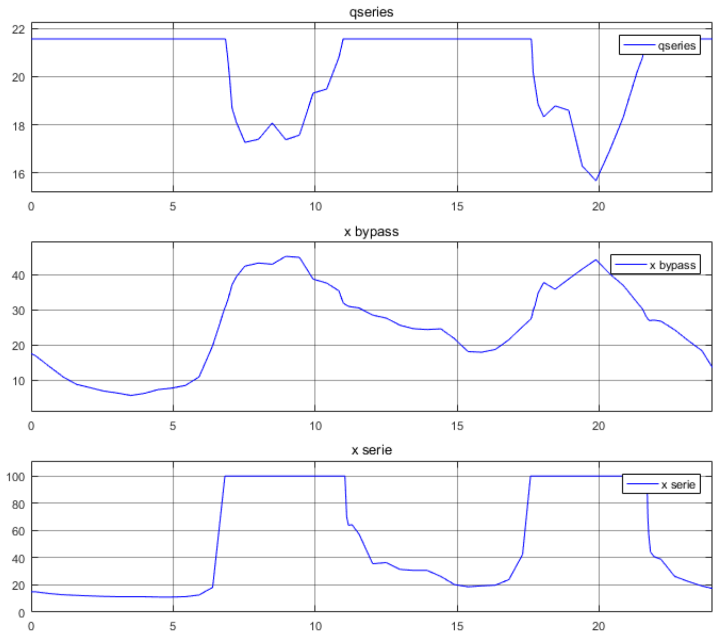

Figure 8.6: valves regulating signals: bpass valve always work in this case, and series also remains fully openend only when H decreases. at the top flow through the turbine a sa reference.

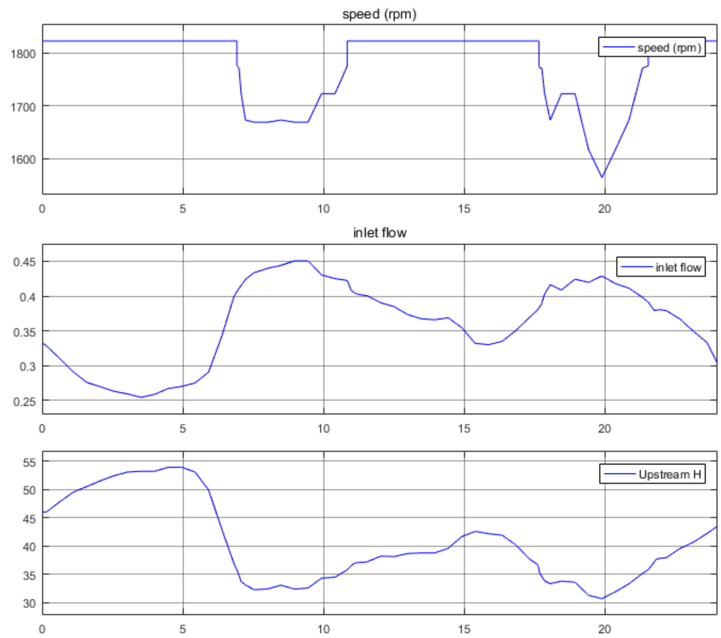

Figure 8.7: speed reference has the same behaviour of head. can be noted that in this situation we work the most of the time at speed limit. middle and bottom we can see the simmetry of the inlet pressure and flow values.

much lower than the nominal.

Power and energy production and is talking of efficiency that we have to approach the simulation results concerning the power production and the productivity of the system. because one thing is talking about the theoretical process and other is talking about the real world, and at the end engineering is always about efficiency improving. since we are working with a mathematical model, that even if derived from empirical measurements remains an abstract one, and for what said when talking about the lack of coherence when calculating efficiency of the turbine in different working conditions than the nominal, we do have to take a lot of care when analysing the following results.
that was about the turbine. then there is the system global efficiency, intended as the turbine together with the mechanical transmission, the generator, the inverter and eventual filters of electric transformers and connections needed to process electricity before it can be injected to the grid. regarding this parameter we should have machinery and test it to have a realistic and coherent value. since here is about simulating the only thing we can do is

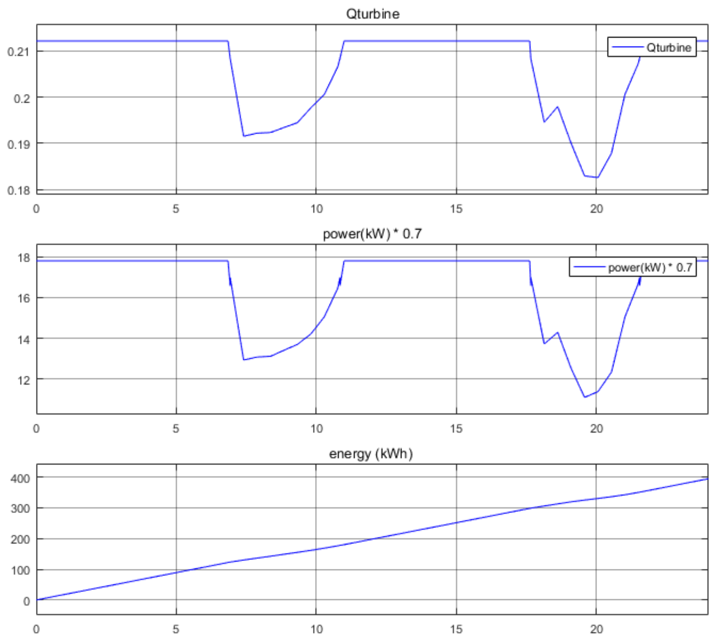

Figure 8.8: power(kW) and energy (kWh) produced in a day, compared with flow in the turbine (top).

looking at bibliography, but in this sense there is quite a wide range of ideas: according to ABB technical guide[22] the efficiency should be always over 80" *Electrical switching with transistors is very efficient, so the efficiency of the frequency converter is very high, from 0.97 to 0.99. Motor efficiency is typically between 0.82 and 0.97 depending on the motor size and its rated speed. So it can be said that the total efficiency of the drive system is always above 0.8 when controlled by a frequency converter.*". at the same time for example Nygren [5] reports that the efficiency of the electrical drive train at BEP (best efficincy point) was of 70.8%, so quite lower. the difference could be in two main aspects:

- the use of the converter as a rectifier (diodes works for an instant instead than IGBT: that means higher losses here)
- the use of the mtor as a generator;

in the end we can suppose a medium system efficiency of 0.75 including all the stated limits of the model.

Power power is computed through its polynomial model. it reflects really well the flow, and makes sense since power depends on flow and speed that both have the same behaviour.

Energy for what regards energy, it is calculated as the integral of power. obviously increases during the daytime. what is relevant here is the final value: we reach a daily energy production of approximately 400kWh. this number does not means nothing maybe since the input data are fantasy and there is almost no connection to reality in this simulation. but at the same time, though, the absolute values are not that far from the parameters of a real turbine or of a real WDS: the pressure values are in hte real range of $5m < H < 70m$, and Q is really variable in WDS depending on our relative position with respect to the spring. so it could be a gross reference of productivity. and in this perspective it can give us the idea of profitability of such a system. we have in fact to remember that every kWh produced this way is an energy amount that otherwise would have been dissipated, is saying thrown away. at the same time can be a good reference to enter the idea that a system like this could power not only a little rural installation: given the standard daily energy consumption of a typical residential user, according to iea [38], is of about 30kWh, while coming to Italy, for example is about 7.5kWh [39]. in the two cases, a pat system like this could supply respectively 13 or 53 residential users.this means that a little village in some mountain area where high H values are available in almost every WDS, could take in account a solution like this. considering its already existing and working WDS as an ideal power source: no emission and basically no environmental impact, a better system managing and energy for many users.

Efficincy for what regard efficiencies two different main efficiency have been calculated:

1. an overall efficiency (OE), computed as the ration between the all available inlet theoretical power. this was computed as:

$$\eta_{overall} = \frac{P(kW)}{Qin \cdot Hin \cdot 9.8}; \tag{8.1}$$

   where P is power produced at the end of the system, and Q in and Hin are the inlet flux values.

2. a relative efficiency(RE), intended as the ratio between the power produced and the overall theoretical power of the fluid that could have entered the turbine but had to be bypassed due to generator speed limit or that could not be processed to serve the BP constraint.

$$\eta_{relative} = \frac{P(kW)}{9.8 \cdot Qmpp \cdot \Delta H}; \tag{8.2}$$

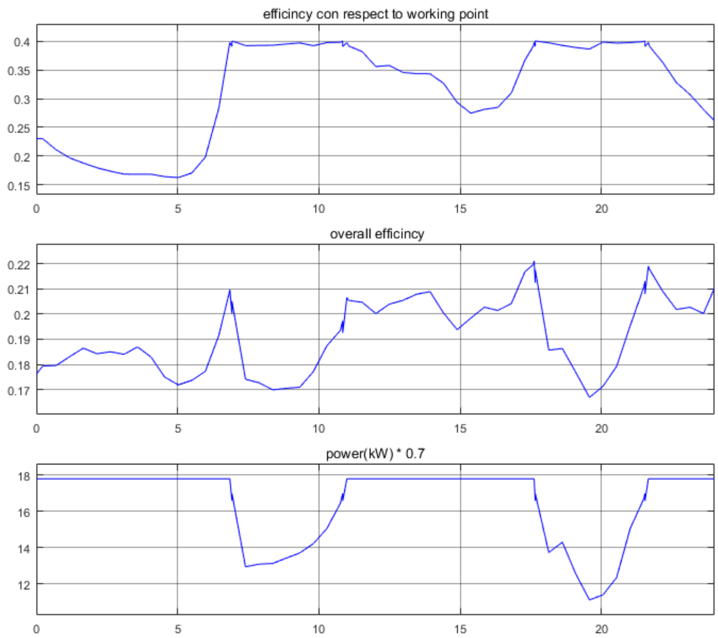

Figure 8.9: overall and relative efficiency for this scenario compared to power production: relative eff is higher when we regulate and power lower.

denominator is the product of Qmpp that is the flow that could be processed with the available DH and gravity acceleration.

simulation results are shown in fig.8.9. it can be seen how the OE increases when the power is at its maximum and head decreases (head is not shown here but can be seen on the other pictures), but then, just when we start to regulate it drops. it is connected to the fact that flow increases a lot in this moment and we actually bypass it since we do not have enough H: this correspond to "losing overall energy". but at the same time the turbine here is working well. this is evidenced by the RE, that in this area, were power lowers, remains high. at the same time it decreases when power is at its maximum: this makes sense since here we are throttling some potentially useful head, due to our generator limits.
with respect to absolute values we can see that the relative efficiency lower from around 0.7, that is the value we decided to place for the case of regulation, to a minimum of 0.17 that though correspond to the higher power production as said. for what regards overall efficiency we assest to a medium efficiency of 0.2, that is a low value but, once again, have to be intended in the optic of a energy recovery system: on one side the alternative is zero power production, on the other such a low value is due to system managing

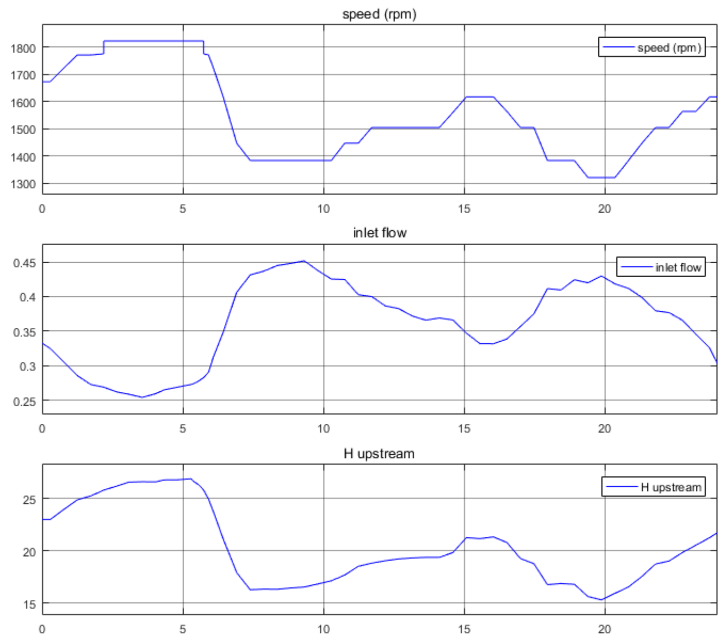

Figure 8.10: speed in this scenario vary more around the nominal value and we work at maximum speed only early in the morning. Q and H are also shown.

requirements, that is our main task in this situation.

Scenario 1: everyday working

this scenario, as said is once again more similar to a real situation, with lower H values. the incoming flux trend is let exactly the same as beffore, only the absolute values of H are changed. as we will see we remains almost all the time in the regulating region. the results are explained in comparison with the previous situation

Parameters comparisons the first interesting thing to be noted is the higher regulation: this can be seen for example in the speed reference that now varies much more. and not only varies, but also in a wider range of speed, crossing the nominal speed.
with regard to the valves we see the series valve works almost all the time fully open. there is just a moment in which have to work due to a high head and flow together situation. this is a good thing, since means we are not dissipating H in the valve, but we are using all of it in power production. Q varies during the day and Q processed from the turbine also, that imply the

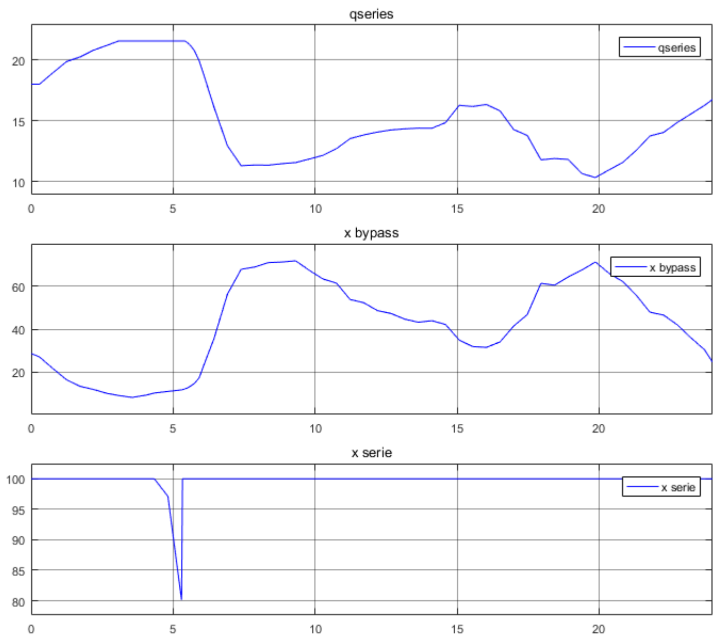

Figure 8.11: valves behavior in everydayworking conditions: series valve almost never plays, being aided by the frequency regulator. bypass instead has it work to do in assuring the bypass the requested inlet flow. at top the flow through the turbine vary during the day and is maximum with maximum head, early in the morning.

speed regulation we saw, and at the same time the bypass valve work: we see it covering wide ranges of opening.

Power and energy coming to power there is not much to say: it follows the head gap. regarding absolute values we see that the maximum values is not that lower with respect with before, and is reached early in the morning, when we work around/on the speed limit curve. the lower production are around 5kW.
regarding energy we can see well the daily power distribution, with higher rates at first, slowly decreasing. the daily production here is of 250kWh, around the half of the other, as predictable from the power expression depending proportionally from H.

Efficiency if OE follows well the other curves of Q,H and P, RE here has a quite peculiar trend: it has lots of oscillations. that could seem strange

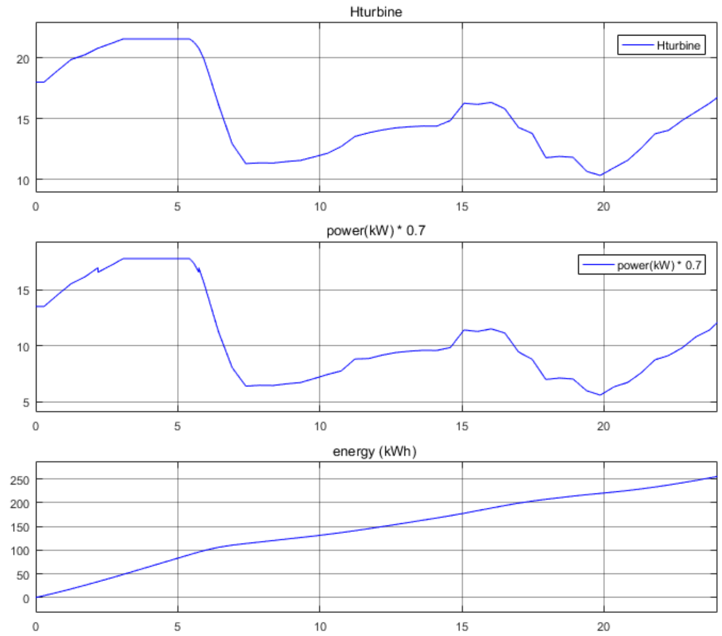

Figure 8.12: head on turbine and power produced have a really similar tendency, that correspond als oto the Q processed by the turbine. energy evidence the lowering of the head during the day.

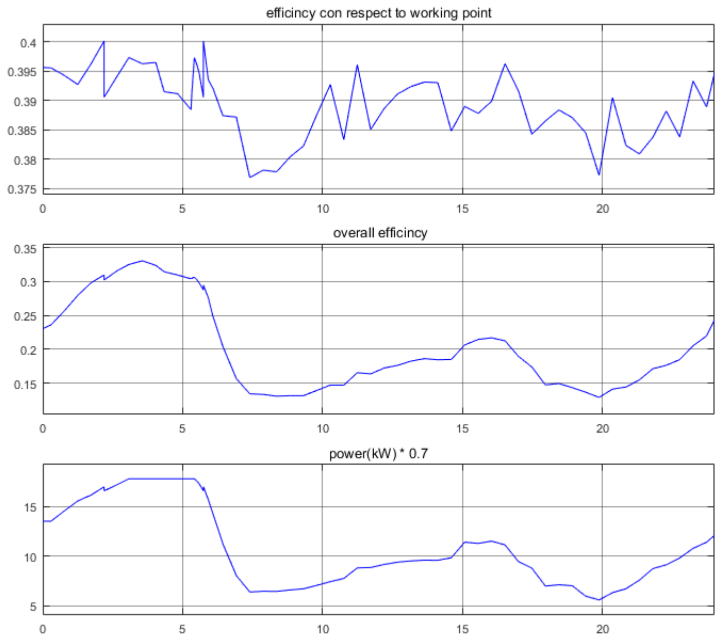

Figure 8.13: relative and overall efficincies compared to power production for scenario 2: everyday working

at first: we should be working on MPPc, should not be working at maximum efficiency? it is not like this: efficiency decreases as far as we go from the BEP, as could be seen in the experimental curves measured by Nygren[5], shown in fig. 8.14. se here we are regulating going up and down the MPPc and RE varies in consequence.

regarding the absolute values we see the medium value of RE is approximately 0.39. this is quite a low value, but is the best we can actually get from the system. idem for the OE, that is quite low, attesting at around 0.2.

A commentary are this values so poor as they seem to be? maybe yes, maybe no, depending on how we look at them. for sure a conclusion from the comparison we can get is: higher head values means higher efficiencies. is saying that maybe with a smaller turbine we would have got higher efficiencies; but perhaps also lower power production, so one point to say is that maximizing power production could produce a decrease in efficiency. that could mean spend more money n a bigger turbine that, with a lower efficiency gives us more energy. here it is a design choice, and in an economical analysis this would appear clearly, for example looking the Pay Back Time value. finally it has to be considered, when for example simulating different

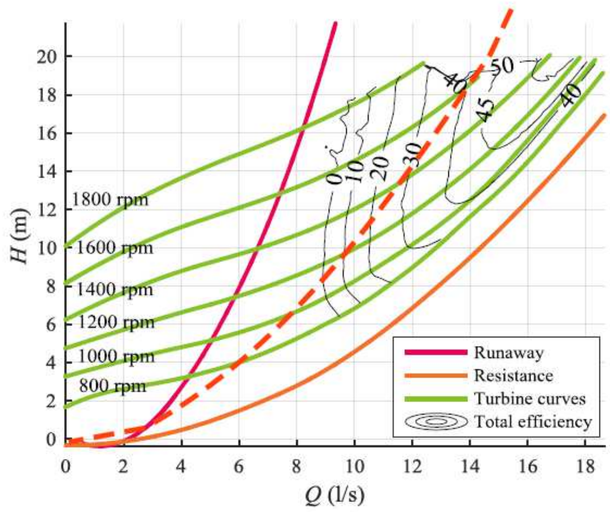

Figure 8.14: efficiency varies following the MPPc, adapted from [5]

turbines in order to choose one for our project, that maximizing power could mean, in this case, having to trouble with quite low efficiencies.

Chapter 9

Conclusions

Lastly we can sum up the track we followed:

1. introducing the PAT idea;
2. exploring its functionality and features;
3. creating a mathematical model that could fit it;
4. describing its typical installation;
5. writing a control logic that could match the objective of power production;
6. trying to create a dynamic model to simulate operating condition;
7. implementing the logic control and making some simulation;

So the problem of modelling and simulating a real system has been approached. Starting from what should have been a practical - problem based case study, that of implementing in a laboratory a controller capable of executing determined tasks, the study has taken more theoretical ways. Joining bibliographical research to and application of different models found in the literature, the mathematical model of the system has been obtained. With this asset, the behaviour of the machine have been studied and some proposal about the logic for the control have been developed, with different situations proposals, tasks, goals and solutions. In the end a dynamic model to simulate a real system has been implemented in a simulation environment and some simulation, based on realistic data have been carried on, leading to interesting and good results. These underlined how the control proposed works, and how the different elements of the system reacted well to the changing input. Also it evidenced how the overall efficiency, in front of a variable inlet conditions, that means working also quite far from the nominal situations, are generally small. At the same time though the relative efficiency reflected that the control match the goal of keeping the efficiency at its theoretical maximum when the flow conditions are available. Moreover some numbers regarding theoretical daily energy production have been obtained, demonstrating the potential of such a system in front of its relative low cost.

In the end an interesting tool for the development of this kind of technology have been developed, and it can be a brick in the construction of its profitability, and its spread. Already alone a PAT system is a cheap and reliable solution that have lots of different potential applications, in many industrial and public sector. The possibility to control it make it even more attractive. Also, the proposed simple control logic, can be easily written in commercial microprocessors, easy to connect to the industrial inverters, and really cheap. This means preserving the main characteristics of this kind of solution, that are simplicity, reliability and low cost, adding the flexibility given by the control. Controlling such a system is, in the end, adding features, without taking anything out, if not having to sum the inverter cost, that is a cost nowadays lowering, and little if compared to the entire system.

Once again is good to remind how such a system could be an effective solution since it is intended for energy recovery more than all, that means that every Wh produced have to be compared to a theoretical alternative solution of energy dissipation. So even little efficiencies have to be looked at with the glasses of a global plant efficiency surely increased, and also with the idea that even in case of no profitable plants, is always about producing renewable energy, that has no environmental impact when operating.

Future development Regarding the continuation of this work, many ideas have popped up in my mind working on this. Some of them could be:

- the expansion of the suitable model proposal and situation studied, passing to real cases and applications;
- the experimental verification of the results and their real effectiveness also in everyday working conditions;
- passing to higher level, for sure the idea of imagining a "smart" water distribution system, that include different pats dislocated in the feasible

nodes: this could means regulating water flow in order to assure the service and maximize power production at the same time;

- the implementation in discrete event, maybe creating a standard POU to be inserted in some openPLC library, and facilitate a PLC implementation, always in this system perspective, could be done (perhaps requiring though a more general and precise model);
- repeating the study with the tools of the predictive control, or adding aspects of meteorology and statistics, and see if different solutions arise.

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